A SYSTEMS ANALYSIS TO DETERMINE AN EFFICIENT CHECKOUT PROCEDURE FOR OPERATIONAL AMPLIFIERS IN AN ANALOG COMPUTER

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A SYSTEMS ANALYSIS TO

DETERMINE AN EFFICIENT CHECKOUT PROCEDURE FOR

OPERATIONAL AMPLIFIERS IN AN ANALOG COMPUTER

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SUMMARY

A systems analysis has been conducted on the "checkout" procedures used in the Georgia Tech Analog Computer Laboratory to ensure the functional reliability of operational amplifiers. The purpose of the study was to determine whether or not a checkout program could be designed that would require less total effort than that presently used while maintaining an equivalent level of equipment reliability and performance.

Checkout data consisting of zero-offset and peak-to-peak noise-amplitude readings were collected from eight operational amplifiers over a five-month period. It was found that zero-offset sample averages had considerably greater dispersion than would be expected from the ranges of the three readings making up each sample. The process mean of the zero offset varied with time and had drift rates from one to eight microvolts per day, depending on the amplifier and other factors; in general, the drift tended to increase the offset from zero. Drift patterns were broken up by readjusting the offset to zero after each checkout. No correlation was found between the zero-offset sample averages and the corresponding peak-to-peak noise amplitudes. Although the zero offset correlated with room temperature over the period of a single day, this relationship was not found to hold for periods of a week or more. Zero offsets were not found to correlate with the power-supply voltages applied to the amplifiers.

A checkout program has been proposed which should be more efficient than the one now in use. A set of decision rules was formulated

to diagnose the general condition of any amplifier; on the basis of a checkout history covering a period of about two weeks, each amplifier can be categorized as being "Class I Stable," "Class II Stable," or "Unacceptable." Process controls are specified for checkouts of amplifiers in each of the three conditions. Those in the first category are stable enough to allow the use of standard control-chart techniques while the others are not; it is suggested that amplifiers having acceptable noise-amplitude levels and relatively low zero-offset dispersion be checked out once a week. Amplifiers with somewhat larger zero-offset dispersion should be checked more frequently, and if such dispersion is very large or if the noise amplitude is great, then the units should be repaired or replaced, or used with extreme caution. Quantitative values are given for the application of the decision rules and process controls, and it has been found advisable in all cases to set the offset to zero after each checkout.

CHAPTER I

INTRODUCTION

The underlying objective of this systems analysis was to determine ways of maintaining a complex piece of equipment, such as an analog computer, at a high level of operational readiness through the employment of efficient "checkout" procedures. In general, checkouts are designed to provide information about the readiness of a system on the basis of measurements made on one or more constituent elements. It is thus implied that a significant change in the value of a parameter of any component within the system will be evidenced by these measurements. The present study is primarily concerned with the effects of component deterioration rather than catastrophic failures--although it is recognized that the latter often correlate with the degree of deterioration attained at the time of such failures.

The experimental portion of this study was carried out with the cooperation of the staff of the Georgia Tech Analog Computer Laboratory. A program was established whose purpose was to examine the existing checkout procedures for a particular class of analog-computer components known as "operational amplifiers," and to determine possible means of reducing the total effort required for such checkouts while maintaining existing levels of equipment reliability and performance. Since any significant reduction in checkout effort would result in increased availability of the computer for problem solving, the program was of considerable interest to the Laboratory itself.

As part of the routine preventive-maintenance procedure followed by the Analog Computer Laboratory, every operational amplifier is given certain standard functional tests at the start of each working day. This checkout process consists of two steps: measuring the amplifier's direct-voltage output when its input is grounded and it is disconnected from a computing circuit (we will hereafter call this a "zero-offset reading"); and, under the same conditions, measuring the peak-to-peak alternating-voltage output (which we will hereafter call the "noise amplitude"). Present checkout criteria require that each zero-offset reading be within plus or minus 100 microvolts of zero, and that the associated noise amplitude be less than 20 millivolts. If an amplifier does not conform to these requirements, it is readjusted; if satisfactory readjustment cannot be accomplished, the unit is removed and replaced.

In keeping with the purpose stated above, an experimental program was designed to answer the following questions:

(a) Is it possible to predict the drift of the zero-offset value as a function of time?

(b) Should the zero-offset value be readjusted to zero after each checkout? If not, when should it be readjusted?

(c) Is there any correlation between the zero-offset reading and the corresponding noise-amplitude value?

(d) Do environmental factors, such as room temperature and power-supply output voltages, correlate with individual zero-offset and/or noise-amplitude readings?

(e) Can an operational-amplifier checkout program be designed which will require fewer than the present number of daily checkouts while maintaining the present level of dependability?

In order to answer these specific questions, it was evident that the study would have to determine the predictive capability of a sequence of checkout readings, and demonstrate the applicability of any checkout program suggested by the last question.

The data-collection portion of the study was conducted from 10 February through 3 July 1959. Sample readings of the zero-offset level and noise amplitude were taken throughout the entire period; in addition, power-supply voltages were recorded after 20 February, and room-temperature values after 9 April. This data-collection effort is discussed in detail in Chapter III.

CHAPTER II

EQUIPMENT

Analog Computers.--A general-purpose, direct-current, electronic analog computer such as the one shown in Figure 1 is a collection of electronic and electromechanical devices so arranged that they may be conveniently interconnected to form a system in which the output voltages vary with time in accordance with a given set of differential equations. The important functional components consist of potentiometers, summers, integrators, multipliers, function generators, resolvers, and recorders. In the average computer problem, summers and integrators far outnumber all other active devices; moreover, both of these major units are formed by connecting appropriate series and feedback elements to individual operational amplifiers.

The state or condition of the computer as a whole is thus largely determined by the condition of the constituent operational amplifiers. Although nonlinear devices such as multipliers, function generators, and resolvers are more complex and less reliable, they are so few in number (comparatively speaking) that they can be given individual checks prior to use; on the other hand, operational amplifiers are so numerous as to preclude such detailed inspection. It appears logical, therefore, to measure the condition of the amplifiers by statistical techniques designed to minimize the risk of using a malfunctioning component in a computer problem, while maintaining checkout economy and convenience.

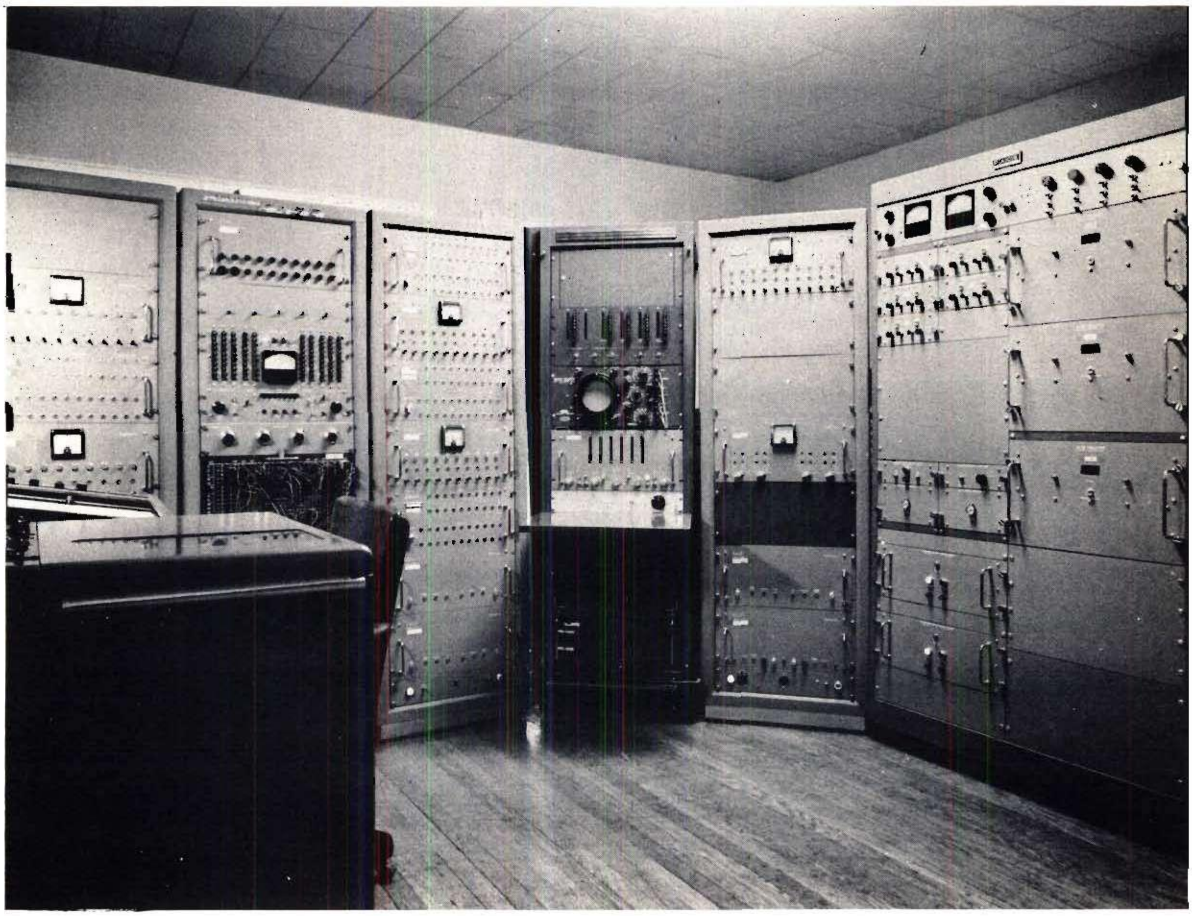

Figure 1. Analog Computer Laboratory at Research Area 4, Georgia Institute of Technology.

<u>Operational Amplifiers</u>.--The operational amplifiers used in the Georgia Tech Analog Computer Laboratory are typical modern, chopper-stabilized, direct-current amplifiers. The theory of operation and design of such devices are adequately described in the literature (1, 2, 3).* Briefly, these amplifiers are designed to deliver an electrical output proportional to a small signal applied at the input; the constant of proportionality (gain) is typically of the order of 10^6 to 10^8.

Principal elements in amplifiers of this type are shown in Figure 2. The input and feedback impedances--marked Z_i and Z_f, respectively--may be chosen to instrument a wide variety of transfer functions for mathematical operations. The most common functional units thus formed are summers and integrators. For summers, both impedances are resistive; for integrators, Z_i is resistive and Z_f is capacitive.

A schematic of the Berkeley Model-1048 operational amplifier used in this study is presented in Figure 3. The packaged unit is shown in Figure 4. When in computer service, ten amplifiers are housed in a mounting panel which provides a meter and necessary switches for zero-offset measurements, as shown in Figure 5. Each such panel is served by a single power supply. The input and output terminals of each amplifier are made available through shielded leads at a centralized patch bay, on which individual amplifiers (and other components of the computer) may be properly interconnected for problem solving.

<u>Drift and Noise in an Operational Amplifier</u>.--Figure 6 depicts the circuit arrangement used for measuring zero-offset voltage in an operational

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*Numbers in parentheses refer to items listed in the Bibliography.

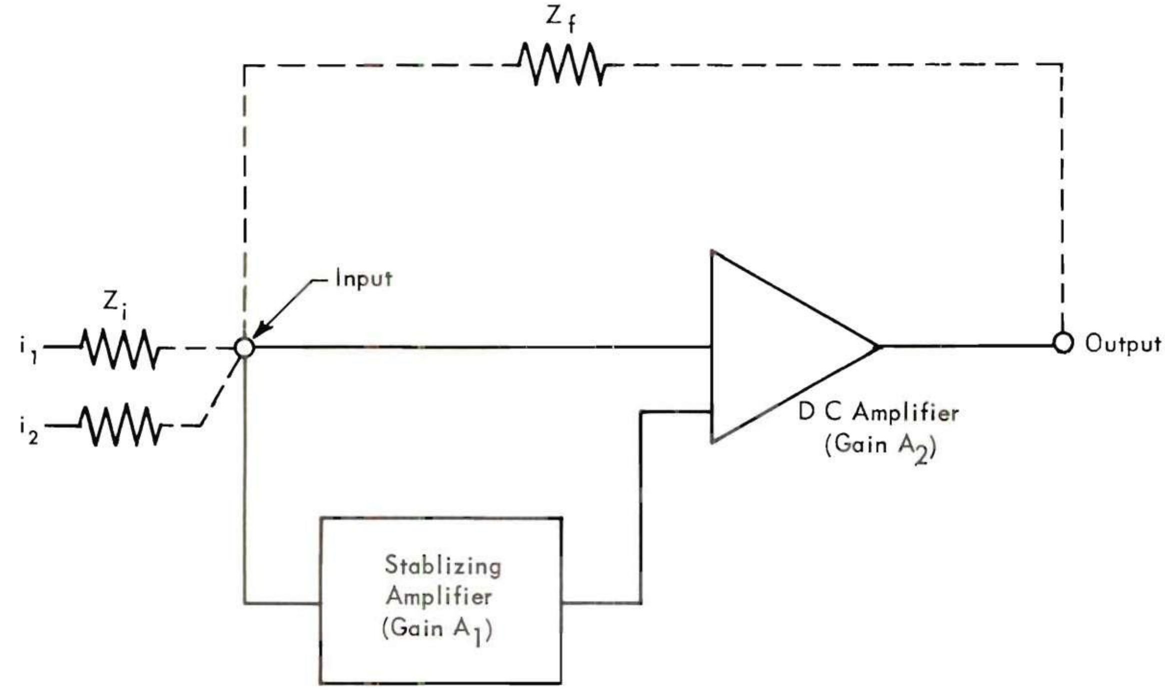


Figure 2. Block Diagram of an Operational Amplifier.

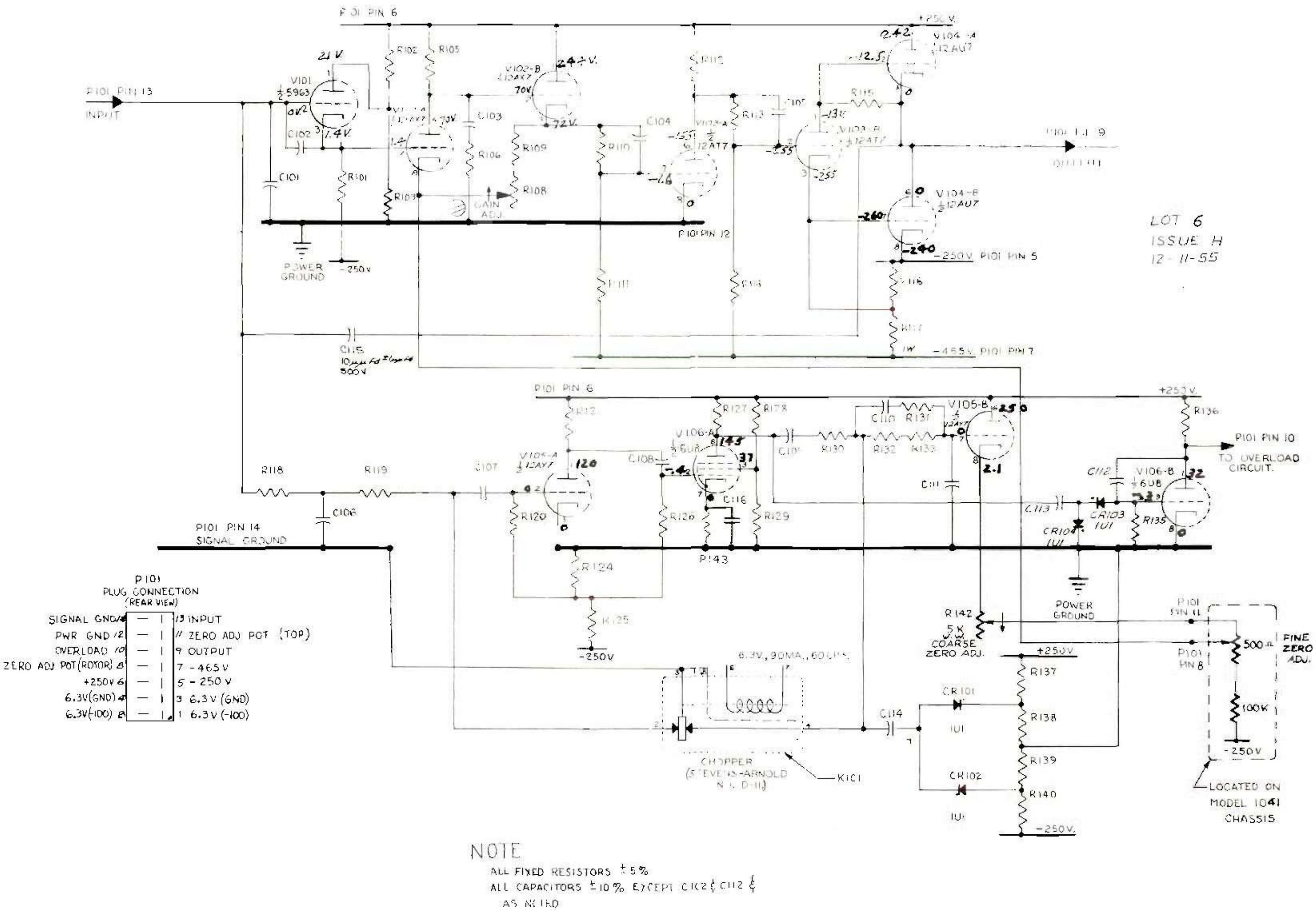


Figure 3. Schematic of the Berkeley Model-1048 Operational Amplifier.

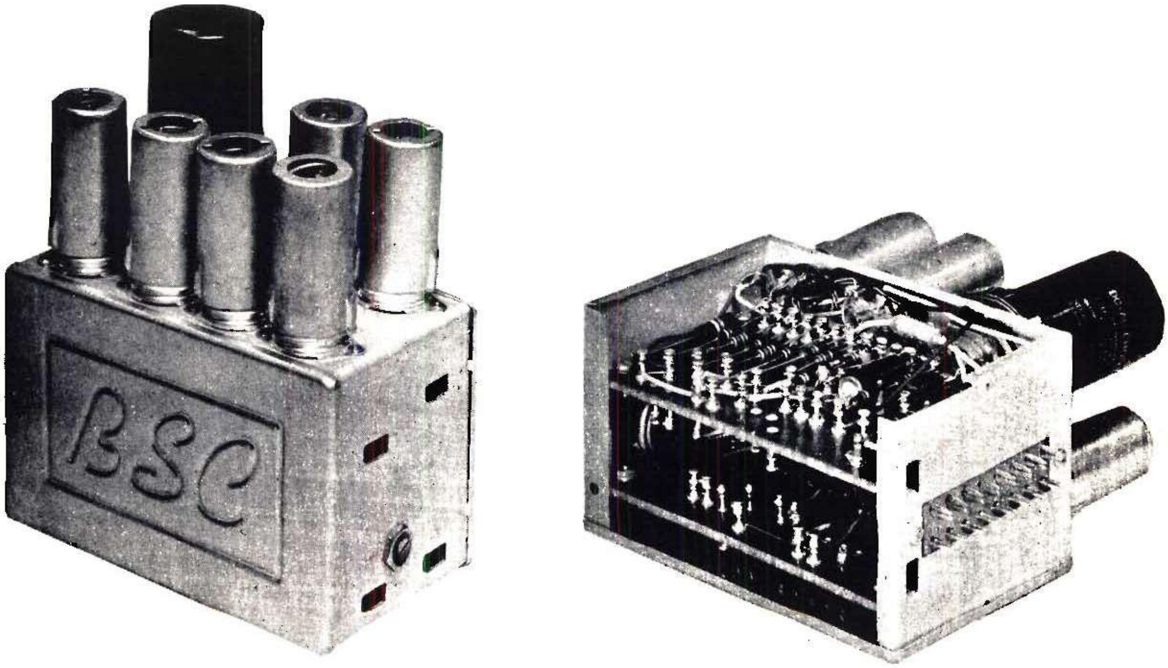


Figure 4. Picture of a Berkeley Model-1048 Operational Amplifier. This Unit is Designed to be Plugged Into the Amplifier Panel Shown In Figure 5 Below.

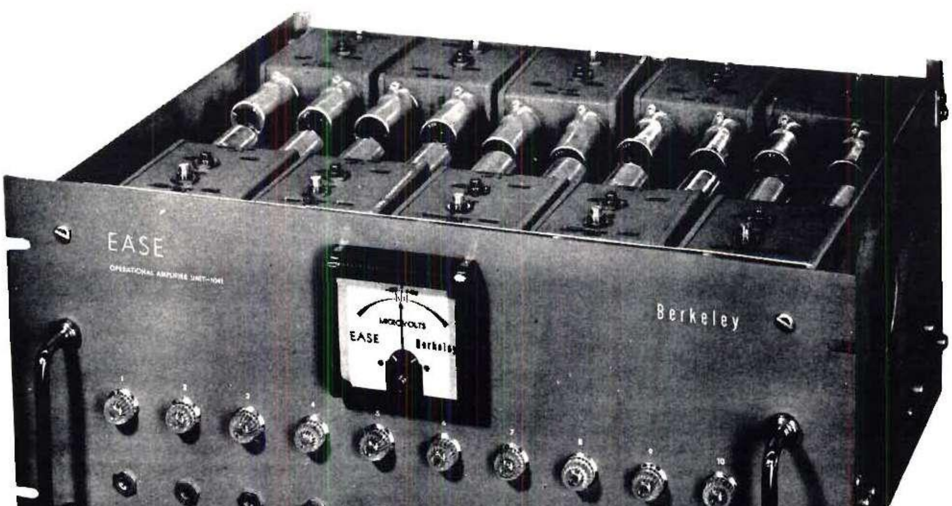


Figure 5. A Berkeley Model-1041 Operational-Amplifier Panel Mounting Ten Amplifiers.

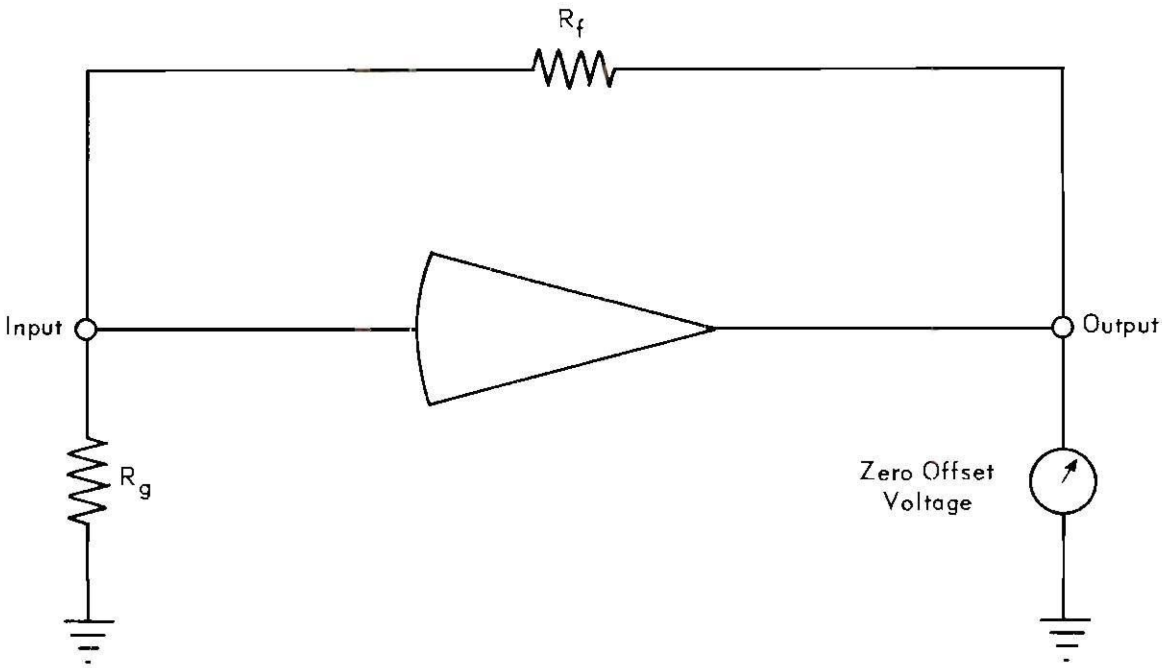


Figure 6. Circuit for Measuring the Zero-Offset Voltage.

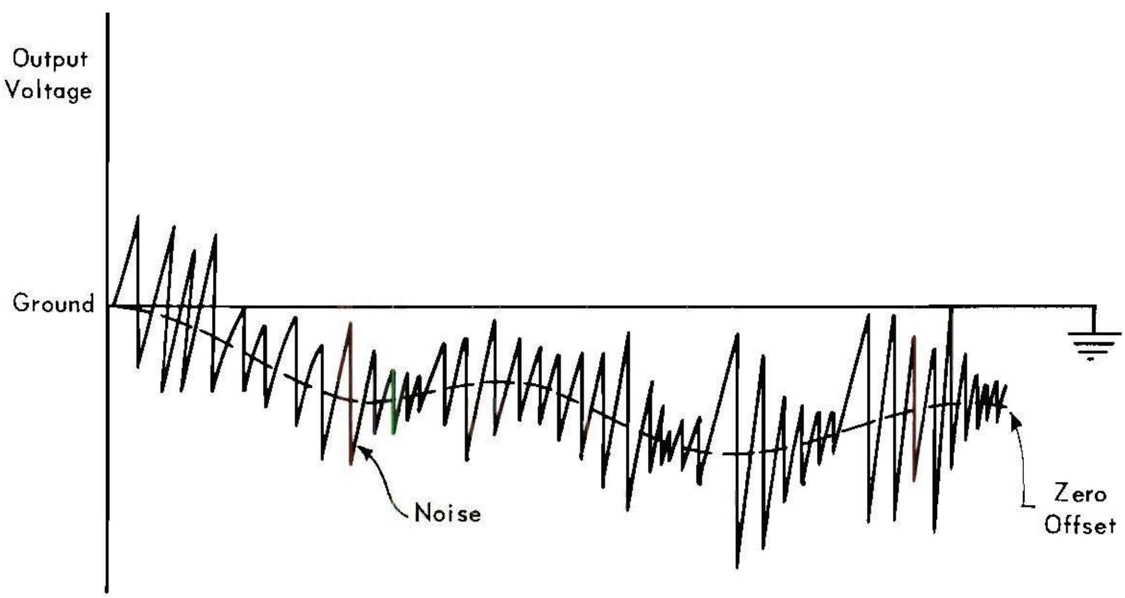


Figure 7. Noise and Drift at the Output of an Operational Amplifier.

amplifier; the input is grounded through a resistance R_g, and a feedback resistance, R_f, is connected between output and input terminals. Any output voltage from an amplifier so connected is undesirable and will contribute errors to problem solutions when used in a computing circuit. These undesirable voltage outputs may be divided into two parts on the basis of the rapidity of fluctuations: "noise" is commonly understood to mean the higher-frequency components, whereas "drift" refers to relatively slow or gradual output variations. This distinction has a very real significance in terms of problem solution errors, since the noise component may be integrated to zero during the course of a solution, but the drift will usually contribute substantial errors through integration. (The term "zero offset," often used synonymously with "drift" in the literature, actually refers to the value of the drift component measured at some particular time.) In general, over a short time interval, the zero offset may be thought of as the direct-current component of undesirable output, and the noise as the alternating-current component. This useful concept, shown graphically in Figure 7, is supported by the usual practice of defining the noise mean as zero.

The noise and zero offset described above can be attributed to various factors, the most important being the following: changes in operating levels of component parts with time, temperature, and humidity; electromagnetic inductive pickup from radio-frequency and 60-cycle sources; ground-resistance variation (both in chassis connections and in earth-ground connections); and internal or component "noise." It is reasonable to consider component-value and ground-resistance changes due to temperature and humidity as factors which affect the zero-offset drift; noise can likewise be ascribed to tube, resistor, condenser, and ground "noise," and to electromagnetic pickup. However, because of the complexity of the problem, it is not possible to determine an exact functional relationship between a particular combination of these factors and the zero-offset and noise outputs. This fact lends support to the contention that the most profitable approach to the problem of determining the condition of an amplifier is through statistical methods applied to zero-offset and noise-amplitude readings.

Measurement of Drift and Noise.--As was suggested in the preceding section, measurements of an amplifier's noise-amplitude and zero-offset voltages provide information about the static condition of the amplifier rather than about its dynamic capability. Consequently, design factors which limit the dynamic capability of these amplifiers are not included in this study. The fact that these limitations (together with mathematical and programming blunders) give rise to errors in the computing process, has received considerable attention in the literature (4).

The operational amplifiers studied during this program were connected as shown in Figure 6 with resistors R_f = 1 megohm and R_g = 1000 ohms, giving the system an overall voltage gain of 1000 and an attendant sign reversal (180° electrical phase shift). Spurious signals generated in the operational amplifier are amplified to an extent dependent on the number of stages passed through from their inception to the final amplifier output. Other zero-offset voltage and noise sources are found in elements comprising the ground loop. The zero offset is read with a voltmeter graduated at -100, -50, 0, +50, and +100 microvolts (as seen in Figure 5). An oscilloscope calibrated in millivolts placed in parallel with the drift meter is used to measure the peak-to-peak noise amplitude.

Environmental parameters that have been measured during portions of this program are as follows: (a) the +450- and -450-volt outputs of the direct-current power supplies serving two operational-amplifier panels, and (b) the ambient temperature in the computer room. In addition, a record was made of comments by the technician on the performance of the equipment each time a set of measurements was taken.

Preventive-Maintenance and Checkout Procedures.--In order to ensure a high level of accuracy the Georgia Tech Analog Computer Laboratory conducts a preventive-maintenance program which includes bench-testing each amplifier every two months, as well as a prompt and efficient repair service.

In addition, and of particular importance to this study, an extensive checkout program is maintained. Every morning the zero offset and peak-to-peak noise amplitude of each amplifier are measured. If the magnitude of the zero-offset reading is greater than 100 microvolts, the amplifier is readjusted to reduce the offset to approximately zero. If this adjustment cannot be made, the unit is removed and repaired. Likewise, the amplifier is repaired if the peak-to-peak noise amplitude exceeds 20 millivolts. Any other operational peculiarity observed during checkout is corrected by either adjusting or repairing the amplifier. As a further means of monitoring the status of the computer components, check runs are made for every program of consequence in order to test the performance of the system and to isolate mathematical and programming errors. These check-run results are then compared with analytically or numerically determined values. In the face of such precautionary measures, a problem is not likely to be run with a malfunctioning component--though it is possible that an amplifier, for example, might be erratic and give the correct results during a check run but develop zero-offset or noise errors during an actual run. The maintenance program described above minimizes the likelihood that this will occur.

Unfortunately, routine daily checkouts for a large analog-computer facility might require prohibitive amounts of time. A less extensive checkout program would obviously be desirable if its use did not significantly increase the probability of failure during a particular computer run.

CHAPTER III

DATA COLLECTION AND REDUCTION

Program.--In order to design an experiment which would provide answers to the questions stated in the Introduction, certain expected relationships between operational amplifiers within the analog computer had to be taken into account--namely, that amplifiers in the computer are not likely to perform identically, but those within a given mounting panel may tend to behave similarly. This latter characteristic is possible because all amplifiers in any one panel are fed from the same power supply and are subject to virtually identical temperature environments. Hence, four operational amplifiers were selected at random from each of two mounting panels; pairs of these amplifiers were arranged to identify the effects of either readjusting or not readjusting the zero-offset after each checkout. The experimental design is summarized in the array below.

	Operational-Amplifier Panel 231	Operational-Amplifier Panel 239
Zero-Offset Readjusted to Zero After Each Checkout	Amplifiers 16 and 19	Amplifiers 26 and 30
Zero-Offset Not Readjusted After Each Checkout	Amplifiers 12 and 17	Amplifiers 21 and 29

At the outset of the data-collection program, these eight amplifiers were marked so that they would not be checked out, readjusted, or tampered with except for collecting data for this study (though their use in computing circuits was permitted). In addition to the recording of numerical information, notes were made of any unusual operational or environmental occurrences, so that the history of each of these amplifiers was accurately known for the five-month data-collection period.

Zero-offset data were collected in samples of three readings. In order that each reading in a sample might be independent of previous ones, the readings were separated by intervals of 15-30 seconds. (This allowed transients to die out after they were generated by the depression of the toggle switch which disconnected the amplifier from the computer circuit and connected it to the meter and ground as shown in Figure 6.) Off-scale readings were so indicated, with their plus or minus directions noted. In cases where oscillations or excessive jitter precluded zero-offset readings, this fact was recorded on the data sheet. Additional instructions to the technician who performed the checkouts for this study program included:

(a) The zero-offset for each amplifier was to be readjusted to zero at the outset of the program.

(b) Readings were to be taken each morning no earlier than one hour after the plate voltages had been applied.

(c) Those amplifiers which were not to be readjusted were to have their adjustment screws covered with tape, and no adjustment was to be made without a direct request from the author.

(d) Those amplifiers which were to be readjusted were to be rezeroed after each sample of three readings.

(e) Zero-offset readings were to be recorded to the nearest 5 microvolts and noise amplitudes to the nearest 1 millivolt.

The single peak-to-peak noise-amplitude measurement was made immediately after the three zero-offset readings had been taken. The technique used for this measurement was to display the amplifier's noise output on an oscilloscope, adjusting the sweep rate to match the average frequency of the noise, so that a relatively stable pattern appeared on the face of the cathode-ray tube. With this technique, the average peak-to-peak noise could be read to the specified 1-millivolt precision quite easily.

Because it was suspected that the observed data behavior might be related to environmental parameters, after 23 February the power-supply output was recorded to the nearest 0.1 volt whenever zero-offset and noise-amplitude data were collected; and, beginning on 9 April, a record was also made of the room temperature to the nearest 0.1 degree centigrade whenever checkout data were collected. It was hoped that observed variations in zero-offset values would correlate with the variations in power-supply voltage and room temperature.

All data were taken as described above, but were collected in three distinct checkout sequences. The initial sequence, which we will designate "long term," consisted of 45 daily samples, collected on various days during a 107-day interval. The second, designated "short term," consisted of samples taken every hour from 9 a.m. to 5 p.m. from two amplifiers on three consecutive days; this sequence was designed to reveal the within-day variation of the zero-offset readings. The third, designated "three week," consisted of samples taken from all the amplifiers at 9 a.m., 1 p.m., and 5 p.m. on consecutive working days for nearly three weeks; this sequence was designed to show variations in zero-offset drift at closely controlled times on successive days of actual computer operation. The durations of the latter two data-collection sequences were necessarily limited, because of inconveniences imposed on the Analog Computer Laboratory by the loss of both technician and computer time.

Table 1. Number and Kinds of Zero-Offset and Noise-Amplitude Data Collected

Data Sequence: Dates From-To	Number Of: Data Days	Number Of: Expected Samples Per Day	Amplifier	Number of Zero-Offset Samples: Sample Size 3	Incomplete Sample Size 1 or 2	Sample Not Readable	Sample Off Scale	Total	Number of Noise-Amplitude Readings
Long Term: 10 Feb.-27 May	45	1	12	41	0	0	4	45	45
			17	43	0	0	1	44	44
			21	25	3	4	13	45	45
			29	33	0	6	6	45	45
			16	42	3	0	0	45	45
			19	45	0	0	0	45	45
			26	36	0	0	9	45	45
			30	34	0	7	4	45	45
Short Term: 12-14 April	3	9	12	26	0	0	0	26	26
			16	26	0	0	0	26	26
Three Week: 15 June-2 July	13	3	12	35	0	0	0	35	35
			17	35	0	0	0	35	35
			21	1	4	20	10	35	35
			29	35	0	0	0	35	35
			16	28	1	6	0	35	35
			19	35	0	0	0	35	35
			26	33	1	0	1	35	35
			30	33	1	1	0	35	35

Table 1 summarizes the number and kind of zero-offset samples collected during these three data-collection series.*

Several features in this table deserve comment:

(a) "Data Days" refer to the number of days on which data was collected.

(b) Expected samples per day are the number scheduled for that data series; complete sampling was not possible in all cases.

(c) Incomplete samples of size one or two were encountered; the missing readings were due to excessive meter jitter and/or oscillations.

(d) It will be noted that the short-term series falls within the long-term interval; as a result, one sample from each of two data days is common to both series for Amplifiers 12 and 16.

The number of environmental readings in each data sequence are summarized below:

Table 2. Number of Environmental Data Collected

Environmental Data	Data Sequence:	Dates: From-To	Number of Observations
Power-Supply Voltage	Long Term:	23 February-27 May	38
	Short Term:	2-14 April	26
	Three Week:	15 June-2 July	35
Room Temperature	Long Term:	9 April-27 May	13
	Short Term:	2-14 April	26
	Three Week:	15 June-2 July	35

*The actual data collected during this study are reproduced in the Appendix.

Zero-Offset Sample-Average Data.--Zero-offset sample averages for all data collected during this program are plotted in Figures 8 through 12. Figures 8 and 9 display data from the long-term series, Figure 10 presents the short-term data, and Figures 11 and 12 show the results of the three-week series. Each figure includes a pair of charts pertaining to amplifiers from the same panel; the upper charts display not-readjusted data and the lower ones readjusted data. Amplifiers are thus paired not only by panel but also by the criterion of whether or not they are readjusted. The same symbol is used to identify data pcints for a particular amplifier in all three series.

The median for each group of not-readjusted data is indicated by a dashed line. It will be noted that the plotted points generally exhibit a drift with time relative to this median. Figures 8a and 9a are broken into relatively small groups by readjustments which were made either because of equipment realignment or because the mean of the zero-offset averages for these amplifiers appeared to have drifted off scale. The one exception was the readjustment on 6 May for Amplifiers 21 and 29 (Figure 9a) after they had just been bench tested and "repaired" (see Amplifier Condition, page 40).

Medians have been plotted for the readjusted data only when they were markedly different from zero (greater than 10 microvolts in magnitude).

Distribution characteristics for the three series are given in Tables 3, 4, and 5. Median values were determined from all data available--including samples that were off scale, samples that were made up of 1 or 2 readings (incomplete samples), as well as samples of three readings; only non-readable checkouts were excluded. These tables also

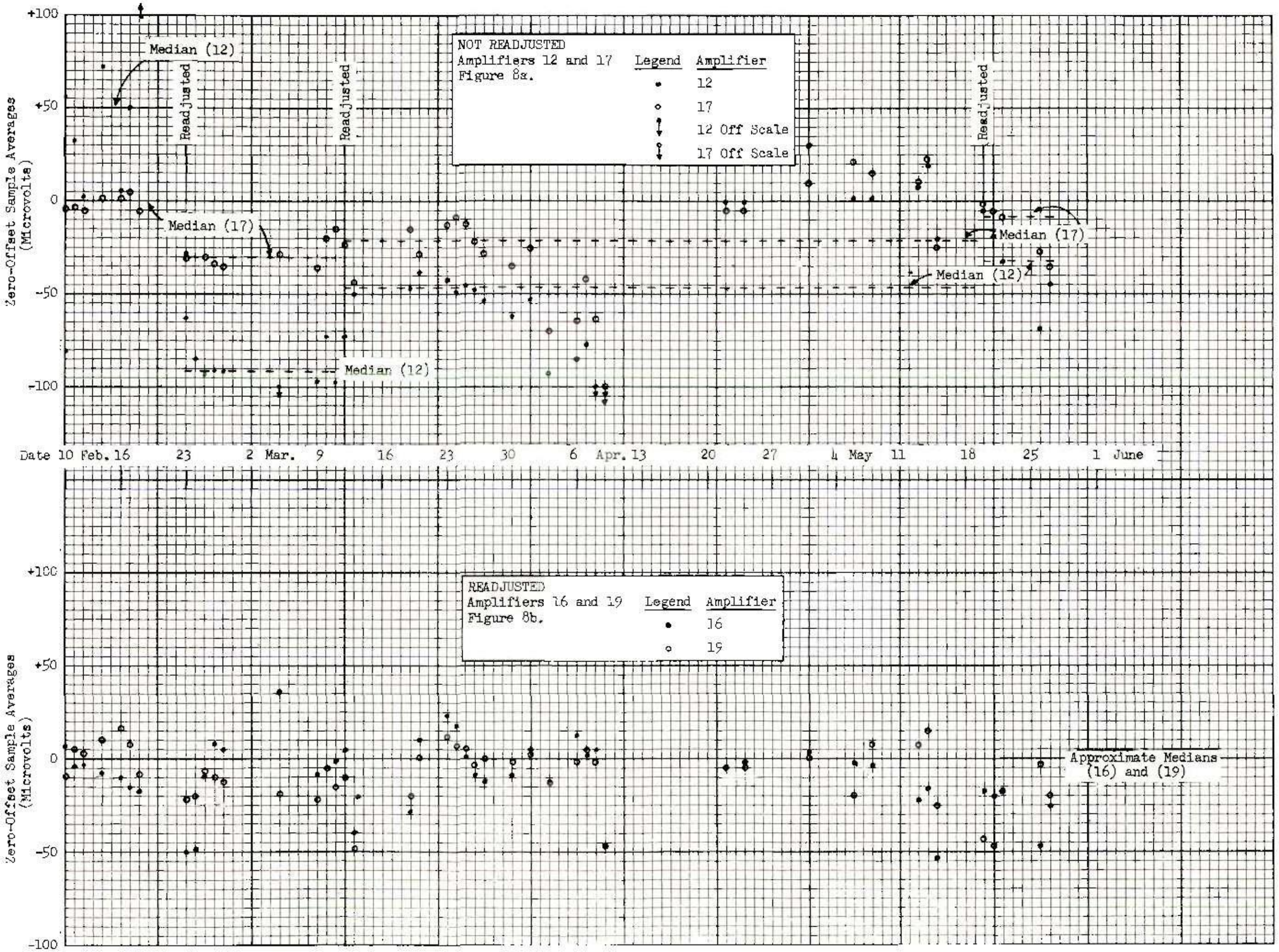


Figure 8. Data Charts of Zero-Offset Sample Averages from Amplifiers in Panel 231: Long-Term Data.

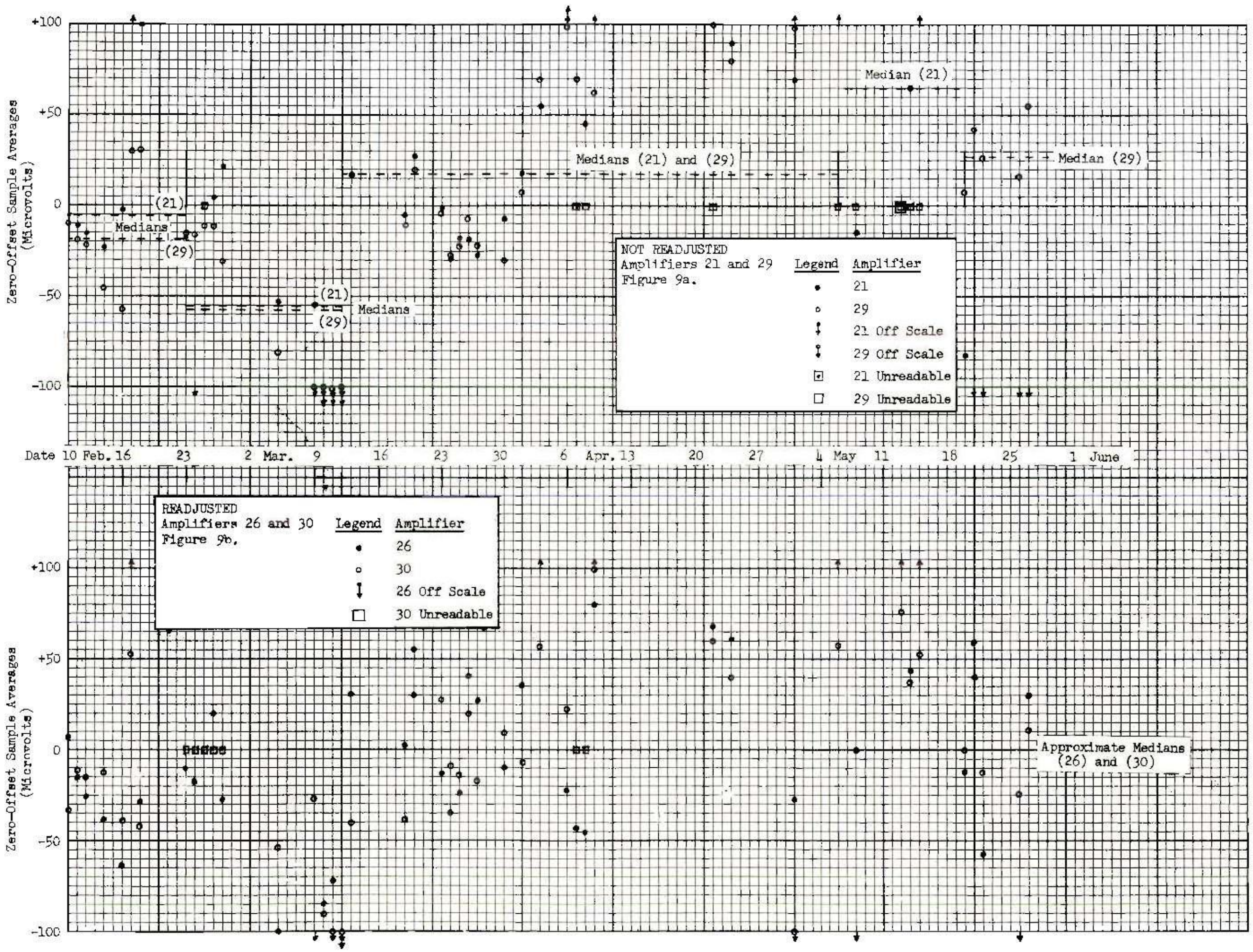


Figure 9. Data Charts of Zero-Offset Sample Averages from Amplifiers in Panel 239: Long-Term Data.

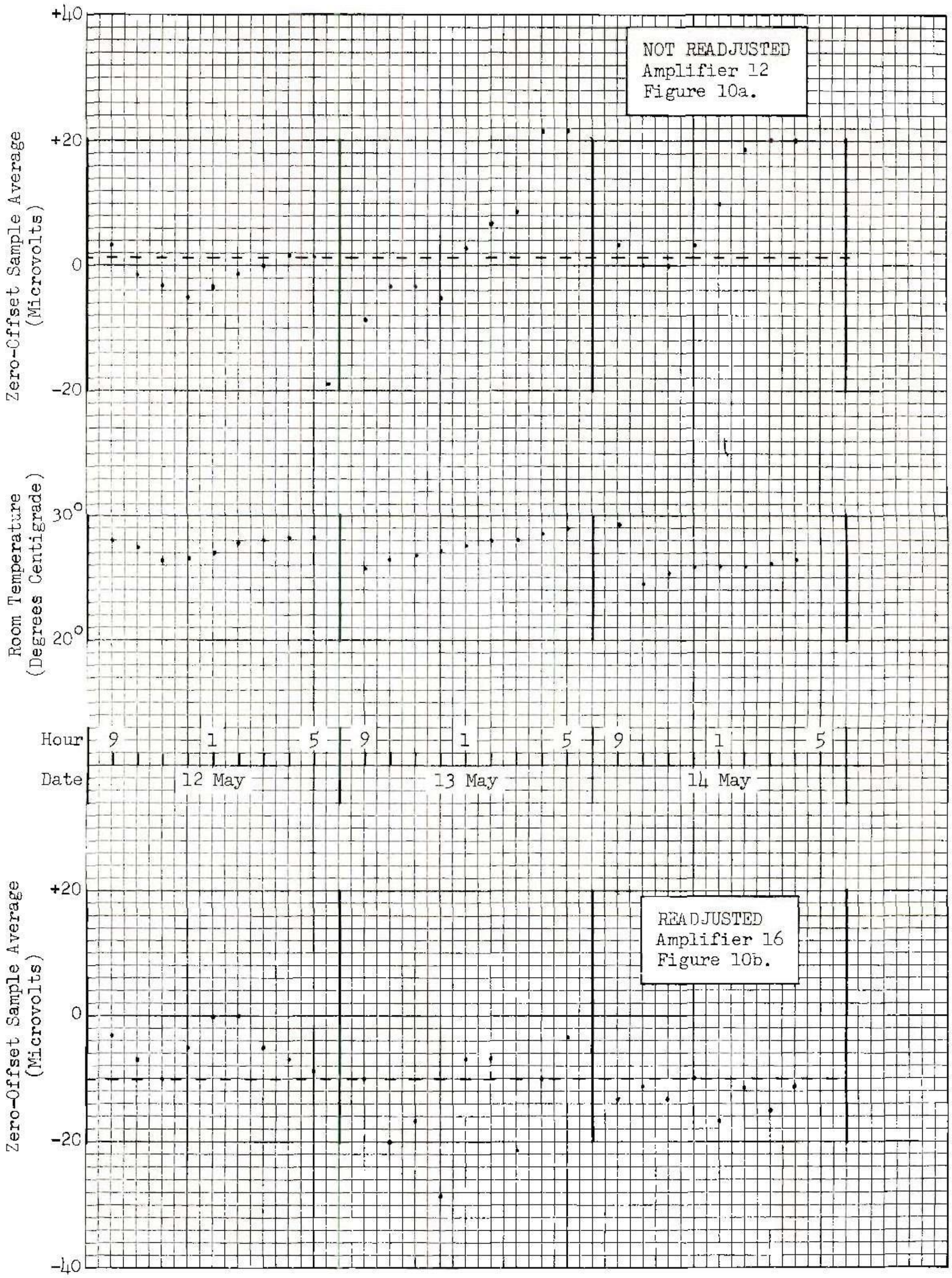


Figure 10. Data Charts of Zero-Offset Sample Averages from Two Amplifiers in Panel 231: Short-Term Data.

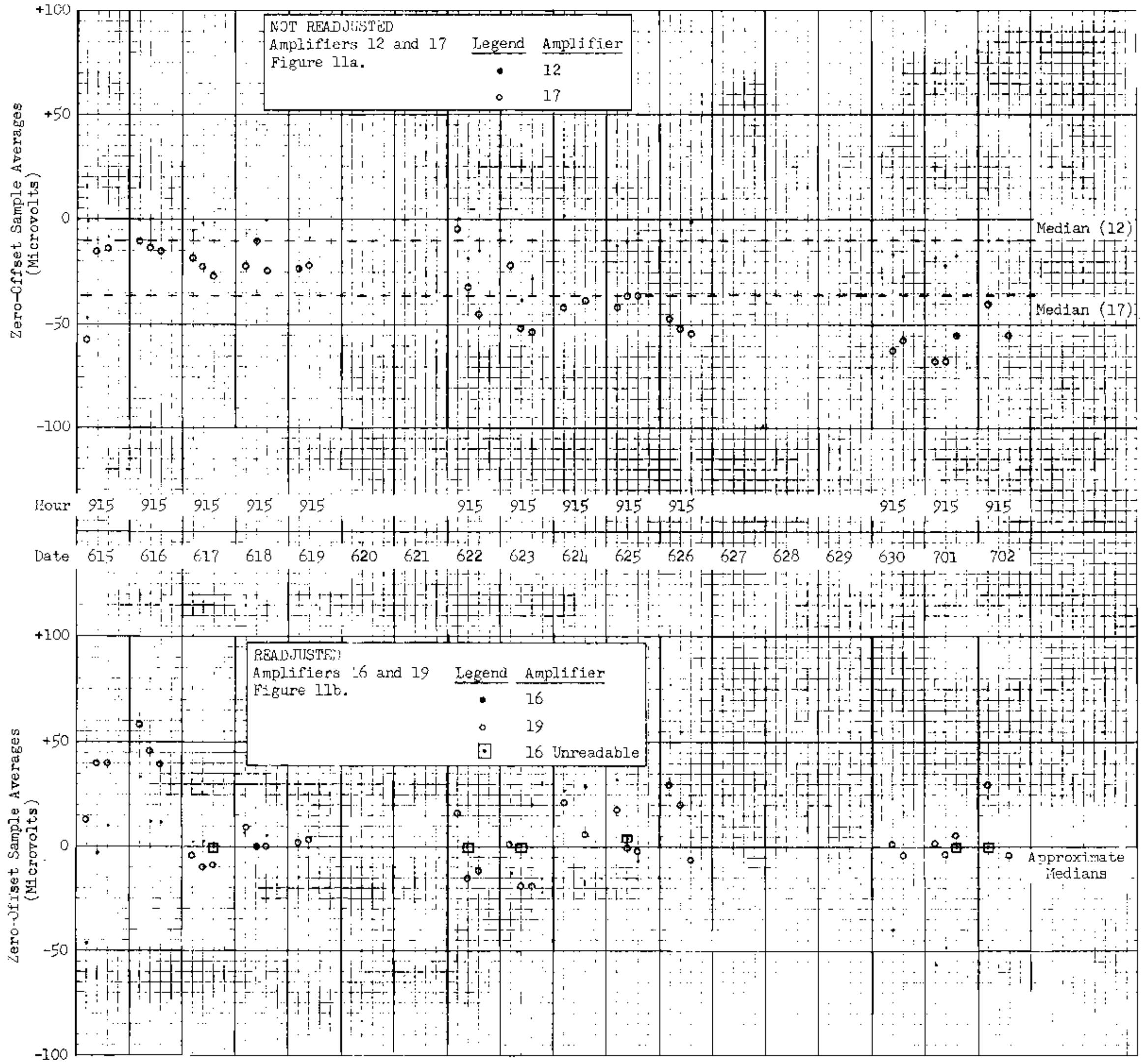


Figure 11. Data Charts of Zero-Offset Sample Averages from Amplifiers in Panel 231: Three-Week Data.

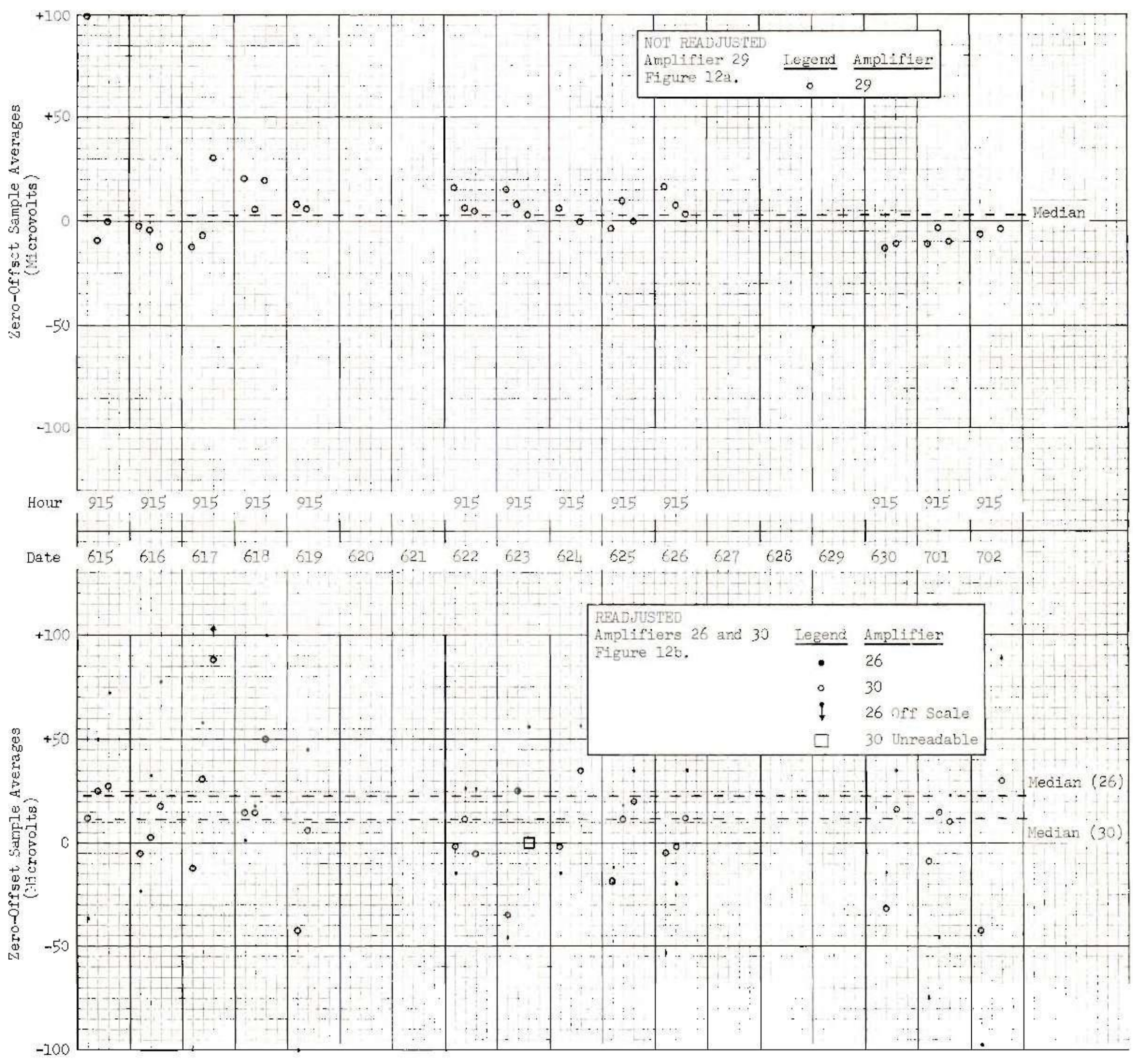


Figure 12. Data Charts of Zero-Offset Sample Averages from Amplifiers in Panel 239: Three-Week Data.

Table 3. Distribution Characteristics of Long-Term Zero-Offset Data

Readjusted	Panel	Amplifier	All Samples		Samples of Size 3			
			N	Median	N	$\bar{\bar{x}}$	$S_{\bar{x}}$	$\sigma_{\bar{x}}$
Yes	231	16	45	- 7.5	42	- 9.4	20	2.9
		19	45	- 5.0	45	- 8.1	16	2.5
	239	26	45	-11.7	36	- 6.4	44	5.5
		30	38	- 7.5	34	+ 4.4	40	3.3
No	231	12	7	+50	6	+37	29	2.0
			10	-92	9	-85	12	4.0
			23	-47	21	-33	35	3.0
			5	-33	5	-34	24	2.4
			45	-	41	-	28	3.0
		17	7	- 3.3	7	- 1.2	4	1.0
			9	-30	9	-28	7	5.7
			21	-22	22	-19	27	4.5
			5	- 8	5	-15	15	5.1
			44	-	43	-	20	4.2
	239	21	7	- 5.0	6	+ 7.5	46	3.4
			9	-55	5	-20	34	8.5
			17	+18	11	+ 8.2	33	5.7
			3	+65	2	+25	57	11.9
			41	-	24	-	36	6.6
		29	7	-18	7	-13	34	3.2
			10	-57	6	-28	28	6.0
			17	+18	15	+21	44	4.2
			5	+27	5	+30	20	2.4
			39	-	33	-	35	4.0

Table 4. Distribution Characteristics of Short-Term Zero-Offset Data

Readjusted	Panel	Amplifier	All Samples (Size 3)				
			N	Median	$\bar{\bar{x}}$	$S_{\bar{x}}$	$\sigma_{\bar{x}}$
Yes	231	16	26	-10	-5.0	9.1	1.9
No	231	12	26	+ 1.7	-0.9	6.6	1.5

Table 5. Distribution Characteristics of Three-Week Zero-Offset Data

Readjusted	Panel	Amplifier	All Samples		Samples of Size 3			
			N	Median	N	$\bar{\bar{x}}$	$S_{\bar{x}}$	$\sigma_{\bar{x}}$
Yes	231	16	29	+ 5.0	28	+ 4.5	29	3.1
		19	35	+ 1.7	35	+ 8.8	17	2.9
	239	26	35	+23	33	+ 5.4	54	6.0
		30	34	+12	33	+ 7.6	26	2.7
No	231	12	35	-10	35	-11	11	2.1
		17	35	-38	35	-36	18	3.2
	239	21	15	-	1	-	-	-
		29	35	+ 3.3	35	5.4	20	2.8

give, based on samples of three readings only, the average of the sample averages, $\bar{\bar{x}}$, the sample-average standard deviation, $S_{\bar{x}}$, computed directly from the usual equation

$$S_{\bar{x}} = \sqrt{\frac{\Sigma\ (\bar{x}_i - \bar{\bar{x}})^2}{N - 1}}\ ,$$

and an estimate of the sample-average standard deviation, $\sigma_{\bar{x}}$, based on the observed range of the readings in a sample. This latter parameter was computed as indicated in the following equations:

$R_i = x_{max} - x_{min}$, where R_i is the within-sample range and x is an individual reading within a sample;

$\bar{R} = \dfrac{\Sigma\ R_i}{N}$, where $\bar{R}$ is the average of the sample ranges and N is the number of samples of three readings;

$\sigma_x = \dfrac{\bar{R}}{d_2}$, where σ_x is an estimate of the standard deviation of x, and d_2 is a range-distribution parameter (5) which is a function of the sample size; this transform is based on the assumption that x is normally distributed with zero mean; and

$\sigma_{\bar{x}} = \dfrac{\sigma_x}{\sqrt{3}} = \dfrac{\bar{R}}{d_2\sqrt{3}}$, which provides an estimate of the standard deviation of the sample averages based on a sample size of 3.

The significance of the observed difference between $S_{\bar{x}}$ and $\sigma_{\bar{x}}$ will be discussed in Chapter IV.

Zero-Offset Data Analysis.--Inspection of the data presented in Figures 8 through 12 reveals certain trends or patterns; these are more noticeable in data from not-readjusted amplifiers than from those that were readjusted. (From here on these will be called "not-readjusted data" and "readjusted data.") Three patterns are suggested from this inspection: (a) data appear to form runs above or below the median, (b) the appearance of data from certain amplifiers suggests a correlation between a sample average and its value the next day, and (c) data from pairs of amplifiers (in the same panel) seem to behave as if an increase in value of the sample average for one amplifier is "followed" by an increase in the value for the other amplifier. Pattern (a) is present in all the data; its existence in both not-readjusted and readjusted data suggests a propensity of the zero offset to drift in a particular direction. This might indicate that there is some long-term drift pattern that varies as a function of time. The appearance of pattern (b) in the not-readjusted data serves to confirm the drift suggested in (a). Pattern (c) implies a correlation between the zero-offset drifts among amplifiers in a given panel.

Each of the observed behavioral patterns was investigated by testing the data with a particular statistic. The methods and results of these tests are described below.

(a) Occurrences of runs above or below the data median were examined by analysis of long-term data from each amplifier. For example, each sample average might be labeled as being above or below the observed data median as follows: aabbaababbba; this gives 7 runs from the 12 samples. The probability of the observed number, or fewer, runs in each sample set has been estimated using tables prepared by Swed and Eisenhart (6) and the results are presented in Table 6.* It may be noted that in every case the probability is relatively small that the data would be grouped into runs of the observed size or smaller, which indicates that the data are non-random. Furthermore, readjusted and not-readjusted data cannot be distinguished in the results of this test, even though this might be expected from an examination of the charts alone.

Table 6. Estimated Probability of Observed Number or Fewer Runs of Sample Averages Above or Below Data Median

Readjusted	Panel	Amplifier	Total Number of Samples	Runs Observed	Probability
No	231	12	38	15	0.0683
		17	38	13	0.0154
	239	21	30	8	0.0023
		29	32	9	0.0030
Yes	231	16	38	14	0.0349
		19	40	11	0.0009
	239	26	38	15	0.0683
		30	36	12	0.0134

*The tables of Swed and Eisenhart give the probability that the observed number, or fewer, runs will occur in an ordered sequence of two groups of data, under the null hypothesis that both groups of data were selected randomly from the same population. In the present application, the data are divided into two groups by the population median, so that it is equally likely that a sample average will be above or below this median. However, the observed median has been used as an estimate of the population median since the latter is unknown.

(b) Although there appears to be some day-to-day correlation between sample averages for a given amplifier if the zero offset was not readjusted, there is considerably less day-to-day correlation, if any, in readjusted data. In order to determine the extent of such correlation, the three-week data were collected and the following statistics computed therefrom: (i) the ranges of sample averages within a day, R_d, where there were three samples of three readings each, and (ii) the differences between sample averages on one day at a given time and on another day at the same time with lags of 1, 2, and 3 days (for convenience, these differences are identified as ranges, R_L, with the subscript indicating the lag used).

Since the nature of the drift of zero-offset sample averages was under scrutiny, no assumptions could be made about the distribution of these ranges (R_d and R_L) of the sample averages. Therefore, the sample distribution functions of the data were used to estimate the median and 90 per cent values for the various lags. Figure 13 presents the observed distributions of R_d and R_L for lags of 1, 2, and 3 days.

Results of the above analysis are somewhat surprising at first glance but appear reasonable upon closer examination. Consider Amplifiers 12 and 17; the 90 per cent levels increase in value with increasing lag, while the median values of the drift remain approximately the same. For both amplifiers, the 90 per cent level ranges of the three samples within a day are greater than the 90 per cent levels with lags of one or two days (it should be remembered that the number of ranges is relatively small). Remembering also that the zero offset was not readjusted and that these differences were taken at roughly corresponding times in the

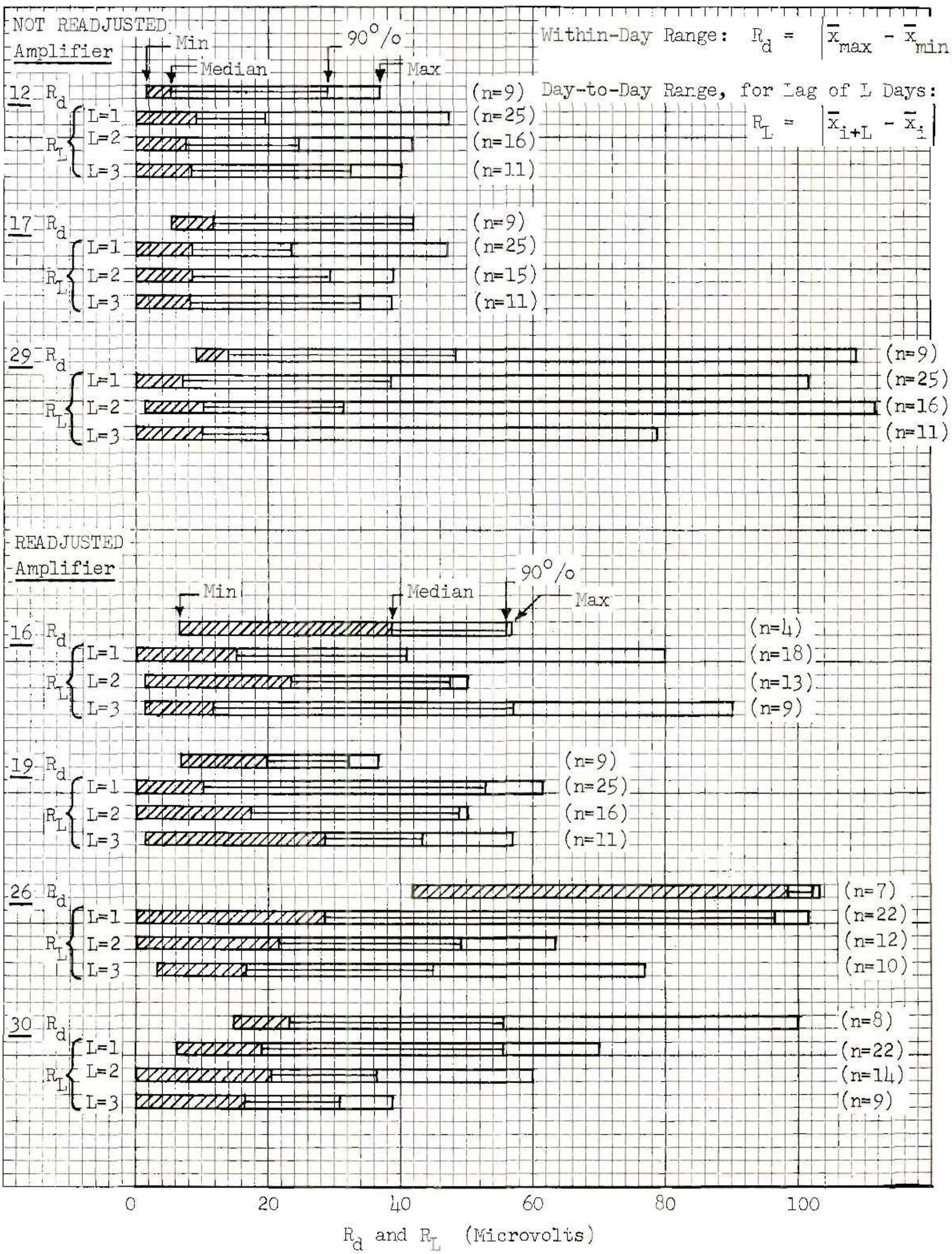


Figure 13. Distribution of Within-Day Ranges and Day-to-Day Ranges with Lags of 1, 2, and 3 Days from Three-Week Zero-Offset Data.

day, this simply means that 90 per cent of the time (for these two amplifiers) the drift within a day is greater than the drift for two consecutive days at corresponding times. The apparent reversal of this effect in the data from Amplifier 29 is inexplicable from this viewpoint; however, it should be kept in mind that the very large values of maxima and relatively small number of differences are such that the 90 per cent levels could very well be distributed in this way by chance.

A pattern of 90 per cent levels like that described above would not be expected from readjusted data. In fact, repeated readjustment might very well reduce the average drift with time. Also, one might expect the within-day range to be of the same order of magnitude as the day-to-day range. These expectations are borne out by the readjusted data--especially from Amplifiers 19, 26, and 30. Data from Amplifier 16 are particularly sparse and therefore the observed results cannot be considered significant.

From this study of ranges, it can be seen that there appears to be a day-to-day correlation between zero-offset sample averages, i.e., that they drift farther in two days than in one day on the average, and that rezeroing the offset after each reading destroys the pattern.

(c) The question of whether or not the zero-offset sample averages from a given amplifier have a propensity to increase or decrease in value according to the way that the value from another amplifier in the same panel changes (that is, to "follow" one another) was examined by counting the number of times this occurred and comparing that with the total number of consecutive data no more than three days apart. From these data, the probability that the observed number or more occurrences of "following" would happen was computed using the normal-distribution approximation to the binomial distribution--where it was hypothesized that the probability was 0.5 that both sample averages would go in the same direction. The results are given in Table 7 below.

Table 7. Probability of Following

Panel	Amplifier Pair	Data Series	Total Number of Samples	Probability That the Observed or Greater Following Rate Will Occur
231	12-17	Long Term	32	0.31
	16-19		34	0.16
	12-17	Three Week	32	0.76
	16-19		21	0.41
239	21-29	Long Term	19	0.05
	26-30		15	0.10
	26-30	Three Week	27	0.00003

From the data presented in this table, there is no reason to believe that a significant amount of following exists for Panel 231, and that the appearance of the data in Figures 8 and 11 can be attributed to the runs investigated in (a) above. The values of sample averages for amplifiers in Panel 239 do follow one another to an apparently significant degree. This can be observed in the three-week data from Amplifiers 26 and 30 shown in Figure 12b in particular. In comparing the two panels it should be noted that, in general, the amplifiers in Panel 231 behaved markedly better than those in Panel 239 (see Tables 1, 3, 4, 5, and 10). Unfortunately, this is the only clue to the reason for the phenomena of following that has been observed and a study of amplifiers from several panels would be needed to identify its cause.

Noise-Amplitude Data.--It was discovered that there is no significant correlation between the zero-offset sample averages and corresponding noise-amplitude values. Figure 14 illustrates this point by showing a plot of zero-offset averages and corresponding noise-amplitude values for the three-week data collected from Amplifiers 12 and 19. This, of course, is not surprising in view of the physical relation between the two (see Figure 7 on page 10 and its associated text on page 11).

One measure of the condition of an operational amplifier is its noise-amplitude level; a peak-to-peak noise amplitude exceeding 20 millivolts is considered excessive since it may introduce errors into a computer solution. Table 8 gives the frequency distribution of noise-amplitude values measured during this program. It will be noted that Amplifiers 29 and 30 had an excessive amount of noise during both the long-term and three-week data-collection periods. The long-term data from Panel 239, including Amplifiers 29 and 30, are shown distributed according to time as well as amplitude interval in Table 9. It will be noticed that there appears to be no significant time dependence for the noise amplitude of the two amplifiers in question.

Environmental Data.--Two environmental parameters were investigated: power-supply voltage and room temperature. Variation of these factors could be expected to affect the performance of operational amplifiers.

Each panel is serviced by a single power supply which furnishes plus and minus 250-volt direct current to each of the amplifiers. Beginning about the end of February, these outputs were measured to the nearest 0.1 volt after each checkout. Throughout this entire program, these voltages deviated from the desired level of 250.0 volts by more than

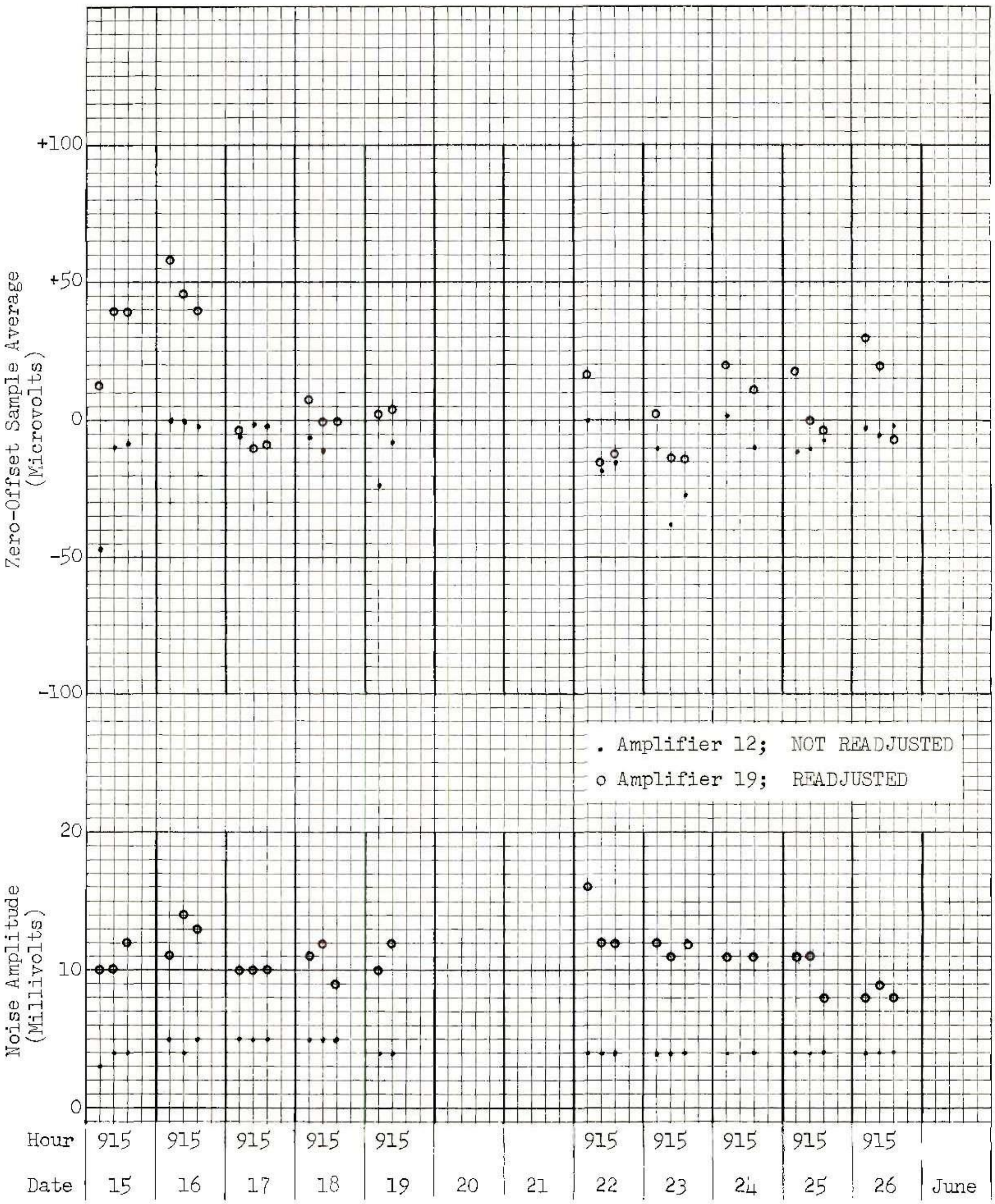


Figure 14. Typical Zero-Offset Sample-Average and Noise-Amplitude Plots: Part of Three-Week Data from Amplifiers 12 and 19.

Table 8. Distribution of Noise-Amplitude Measurements

Panel	Amp.	Data Series*	Class-Frequency Distribution (Amplitude Intervals in Millivolts) 0-20	21-100	101-200	>200
231	12	L.T.	44			
		T.W.	35			
		S.T.	26			
	17	L.T.	46			
		T.W.	35			
	16	L.T.	46			
		T.W.	35			
		S.T.	26			
	19	L.T.	43	1	1	1
		T.W.	35			
239	21	L.T.	44		1	
		T.W.	35			
	29	L.T.	1	32	11	1
		T.W.			34	1
	26	L.T.	44		1	
		T.W.	35			
	30	L.T.	27	8	10	
		T.W.	14	8	9	3

*L.T. = Long Term
T.W. = Three Week
S.T. = Short Term

Table 9. Noise-Amplitude Time-Frequency Distribution from Long-Term Data

(Amplitude Intervals in Millivolts)

Dates		Readjusted						Not Readjusted					
		Amplifier 21			Amplifier 29			Amplifier 26			Amplifier 30		
From	To	0-20	21-100	>100	0-20	21-100	>100	0-20	21-100	>100	0-20	21-100	>100
10 Feb.	22 Feb.	7	0	0	0	7	0	7	0	0	3	0	4
23 Feb.	8 Mar.	6	0	0	0	5	1	6	0	0	1	0	5
9 Mar.	22 Mar.	7	0	0	0	7	0	7	0	0	4	3	0
23 Mar.	5 Apr.	8	0	0	0	7	1	8	0	0	8	0	0
6 Apr.	19 Apr.	4	0	0	0	3	1	4	0	0	3	1	0
20 Apr.	5 May	2	0	1	1	2	0	2	0	1	1	2	0
6 May	17 May	5	0	0	0	0	5	5	0	0	5	0	0
18 May	27 May	5	0	0	0	1	4	5	0	0	2	2	1

1.0 volt only six times. The worst two readings, -246.4 and +251.1, were observed on 20 and 24 March, respectively, for the power supply serving Panel 231; the other four such readings were +251.1, +251.1, +251.2, and +251.3 which occurred in the three-week data from Panel 231. No correlation was observed between individual values of sample averages and the power-supply voltages. Even the extreme noted (-246.4) did not appear to affect the corresponding sample averages in a predictable manner (see Figure 8a). In addition, the checkout condition of the amplifier panel could not be correlated with these power-supply voltages; amplifiers in Panel 239 behaved relatively poorly with a stable power supply while amplifiers in Panel 231 behaved better with a less stable power supply.

Correlation between room temperature and zero-offset sample averages was found--provided the data were taken relatively frequently and the zero offset was not readjusted. Figure 10a shows a plot of the short-term not-readjusted data taken once an hour and a corresponding plot of temperatures; a high degree of apparent correlation will be noted. The correlation coefficients between temperatures and sample averages are of the order of 0.9 for the first two days; however, an anomaly in the data caused the coefficient to drop sharply (to about 0.05) for the third day. An inspection of the day-to-day data reveals distinct changes in the median values of the sample averages of about 5 microvolts from the first to second days, and less than 4 microvolts from the second to third days, while there is only a 0.5-degree centigrade difference between the median temperatures of the first and second days and about 1.5-degrees centigrade difference between the medians for the second and third days. These are, however, sparse data on which to draw conclusions.

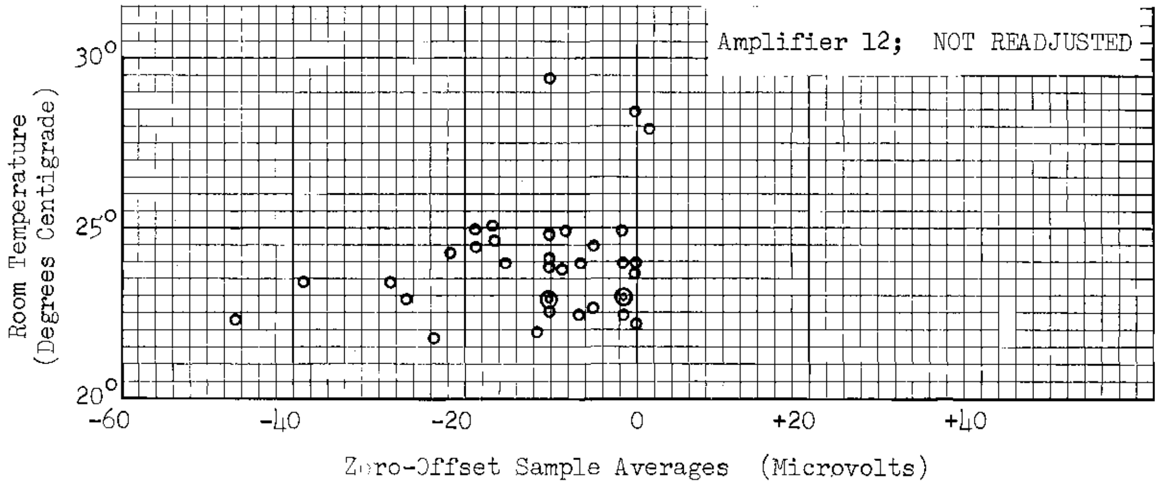
The three-week data provided additional information on this subject. An attempt to rank correlate the daily temperature ranges, R_t, and the range of daily sample averages, R_d, showed that while there is a distinct tendency for large (upper 1/3) values of R_t to correspond to large R_d, there appeared to be no correlation between R_t and R_d for smaller values. Figure 15 shows scatter diagrams of temperature and zero-offset sample averages for the three-week data from Amplifiers 12 and 16 (the same two used in the short-term study). Neither shows any significant correlation.

It is evident from the above considerations that temperature influences are strong within a time interval of the order of a few hours, but become masked by other effects for longer periods of time. Therefore, the value of $S_{\bar{x}}$ for Amplifier 12 in Table 4 might be considered an estimate of the dispersion due to temperature if the observed day-to-day effect is ignored.

Amplifier Condition.--In addition to the data described above, certain general information is needed to complete a picture of the performance of the operational amplifiers used during this program.

The first is that during the long-term data-collection sequence Amplifiers 29 and 30 were removed, bench tested, and repaired. This operation is described in the technician's notes quoted below:

> May 5. Amplifiers 29 and 30 were removed from the computer for overhaul. Each amplifier was carefully checked beginning with tubes. Several tubes in each amplifier had emission values quite close to the lower limit of the established criterion for the Model-1048 amplifiers, but they did meet the requirements so were not replaced; the tubes replaced in each amplifier were--Amplifier 29: 12AU7, 12AX7, and 12AV7; and Amplifier 30: 6U8. Amplifier 30 worked very well when its gain and zero-offset level were checked. Amplifier 29's output waveform was badly distorted, noise output very high, and it



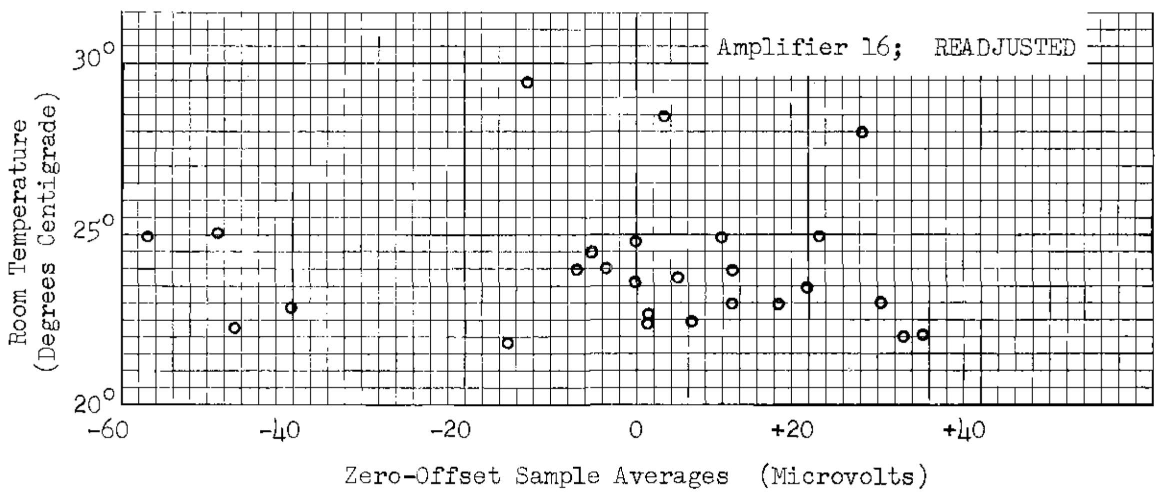


Figure 15. Scatter Diagram of Zero-Offset Sample Averages Versus Temperature from Three-Week Data.

would not respond to normal corrective adjustments. Sometimes a particular vacuum tube will not perform satisfactorily in a particular amplifier even though it is a new tube with high emission. When this happens, another tube is substituted until the amplifier is responding properly. This procedure was tried on Amplifier 29 and appeared to solve the problem; but, being suspicious, I ran the amplifier for several hours in the test jig under 2/3 load. No malfunctions were observed during this period so the amplifier was replaced in the computer and coarse-zeroed after a suitable stabilizing period. The next morning when all the operational-amplifier zero-offsets were checked, Amplifier 29 was jittering badly and had a high noise-amplitude output. There apparently is a component failure other than vacuum tubes.

Despite the comments about Amplifier 29, neither this nor any other amplifier used in this program was removed from the computer for the rest of this program.

At the end of the data-collection program, the technician was asked to comment on the condition of each amplifier. The following are his remarks:

Amplifier 12. Still operating with little day-to-day drift and very small amount of output noise as observed on the oscilloscope. This amplifier would be quite satisfactory for use in problem-solving circuits.

Amplifier 16. This amplifier developed a lot of jitter and noise during the final stages of the experiment. Its jitter and noise output are presently so bad that it should not be used in any problem-solving circuit.

Amplifier 17. Although this amplifier's noise has consistently been higher than average throughout the experiment [but less than 20 millivolts; see Table 7], it is still a stable and useful unit. Its noise is not of a random nature attributable to failed or nearly failed components, but instead more likely due to the internal cabling of the computer (e.g., hum pickup).

Amplifier 19. This amplifier is and has been much the same as number 17; however 19 also contains random noise in its output. This is a condition quite common and not easily eliminated in direct-current amplifiers, and doesn't seriously impair its usefulness in problem-solving circuits.

Amplifier 21. This unit is best described as erratic. One day it will appear to be normal and useful, only to be the exact opposite for the next 2-3 days. In its present condition, it shouldn't be trusted in any circuit where accuracy is important. It should be repaired.

Amplifier 26. The amplifier is sort of a so-so unit. While it can't really be considered either very good or very bad, it is entirely suitable for use in solving problems.

Amplifier 29. This amplifier has failed. It should not be used in solving problems and should be removed from the computer for repair.

Amplifier 30. This amplifier is no better than Number 29, and the same remarks apply to it.

On the basis of these comments, we can place these eight amplifiers into three groups as shown in Table 10. As indicated, Amplifiers 12 and 17 have excellent performance records; this also applies to 16 until the middle of June. Amplifier 19 has no record of abnormal behavior to correlate with the observed random noise in its output. Throughout the program, Amplifier 26 has acted in an erratic fashion. Amplifiers 21, 29, and 30 were plagued with trouble from the outset of this program; subsequent to their "repair" on 5 May, Amplifier 30 did not improve and 29 became noiser.

Table 10. General Condition of Amplifiers

Condition	Amplifier
Good	12 16 (until June 17) 17 19
Fair	26
Unacceptable	16 (after June 17) 21 29 30

CHAPTER IV

RESULTS

Zero-Offset Data Model.--A general mathematical model of a zero-offset reading may be written as follows:

$$x_{ij} = \mu + \delta_i + \varepsilon_{ij} \quad ,$$

where $i = 1, 2, 3, \ldots$ identifies the sample,

$j = 1, 2, 3$ observations within a sample,

x_{ij} is an individual zero-offset reading,

μ is the overall process mean,

δ_i is the between-sample variation, and

ε_{ij} is the within-sample variation.

From this, the model for the average of the i^{th} sample, $\bar{x}_i$, can be written:

$$\bar{x}_i = \mu + \delta_i + \bar{\varepsilon}_i \quad ,$$

where $\bar{\varepsilon}_i$ denotes the average of the variations within the i^{th} sample.

In the last chapter it was pointed out that the within-sample variation could be expected to be normally distributed, since there is no reason to believe that the zero-offset process changes during a sampling period; in other words, $\bar{\varepsilon}_i$ can be assumed normally distributed with mean zero and variance σ_ε^2. An examination of Figures 8 and 9 will suggest that, at least in the cases where the amplifiers were not readjusted, δ_i

may not be normally distributed. From the standpoint of the equipment, it seems reasonable to expect the zero-offset mean, which is estimated by the sample average, to behave as indicated in Figure 7. This suggests that the factor $\mu + \delta_i$ is some function of time, and may be considered to have a distinct value for each sample. Thus,

$$\mu_i = \mu + \delta_i \quad ,$$

where μ_i denotes the zero-offset process mean at the time of the $i^{\underline{th}}$ sample. The model for the $i^{\underline{th}}$ sample average now becomes:

$$\bar{x}_i = \mu_i + \bar{\varepsilon}_i \quad .$$

Let us now consider this last model in view of the data. Tables 3, 4, and 5 show that $\sigma_{\bar{x}}$, the standard deviation of the sample averages based on the ranges of three zero-offset readings within each sample, is considerably smaller than $S_{\bar{x}}$, the standard deviation computed from the sample averages themselves. Moreover, $\sigma_{\bar{x}}$ is much less sensitive than $S_{\bar{x}}$ to an increase in duration of the data-collection period, which tends to increase both standard deviation values. It follows that the estimate of μ_i from sample averages is relatively precise compared to the variation in the sample averages; hence, the observed sample-average dispersion for data collected over a long time period serves as an estimate of the dispersion of μ_i over an equivalent time period.

It will also be noted that the readjusted data cannot be distinguished from not-readjusted data merely by inspecting the dispersion. The only clear distinction between the readjusted and not-readjusted processes is that the averages or medians of readjusted data are relatively near zero--a not unexpected result. In other words, readjustment moves the process mean (μ_i) to within $\pm 3\sigma_x$ of zero but apparently does not affect the dispersion of the sample averages by a noticeable amount.

Readjustment has the effect of breaking up apparent drift patterns, though it does not appear to change an amplifier's propensity to drift in a given direction. As a result, readjusted zero-offset sample averages are grouped in runs above and below their median in much the same way as the corresponding not-readjusted data. Table 6 gives an estimate of the probability that the observed number (or fewer) runs of sample averages would occur if the drift from any point, positive or negative, were equally likely; it will be noticed that this probability is in every case quite small.

Of the environmental factors considered, only room-temperature variation makes an identifiable contribution to the value of $S_{\bar{x}}$. The effect of this factor becomes significant when the sampling period is short (of the order of a few days); however, over a long period of time, the effects of within-panel and within-amplifier variations make the largest contributions. Within the limits encountered in this study, power-supply voltage variations do not seem to affect the value of either zero offset or noise amplitude. The noticeable correlation in behavior between amplifiers in the same panel is doubtless due to their having virtually identical temperature and electromagnetic environments (as well as a common power supply).

Noise-Amplitude.--As might be suspected from the nature of the peak-to-peak noise amplitude, it does not appear to correlate with the value of the zero-offset sample average. The two amplifiers that have exhibited large noise amplitudes will be discussed below in connection with the application of proposed decision rules.

Decision Rules.--The purpose of this study was to investigate the behavior of operational-amplifier zero-offset and noise-amplitude readings to see if some method could be found for reducing checkout effort without increasing the chance that these parameters would exceed acceptable tolerance limits during normal computer operation. The tolerances were given as:

(a) Plus and minus 100 microvolts for zero-offset readings, and

(b) No more than 20 millivolts for peak-to-peak noise-amplitude values.

The two characteristic performance parameters have been examined separately, although from an operational standpoint both tolerances must be met simultaneously in order to use an amplifier in a computing circuit. Unfortunately, zero-offset and noise-amplitude readings from an amplifier tend to vary in such a way that a single checkout does not give a realistic measure of an amplifier's condition. It is now evident that the condition of an amplifier can be determined only by a series of checkouts covering a period of a week or more. However, once this condition has been ascertained there is sufficient process stability that the performance can be predicted statistically for a limited additional time. It is therefore proposed that all amplifiers be examined for an initial period to gather historical performance data and, then, that the condition of each amplifier be categorized on the basis of diagnostic criteria described below. Furthermore, a definite process control procedure has been established for the subsequent treatment of each amplifier, according to its category.

It was noticed that certain amplifiers (e.g., Number 19) were favored with relatively low zero-offset dispersion and a consistently acceptable noise-amplitude level throughout this program. The low dispersion resulted in few, if any, off-scale zero-offset readings (i.e., magnitude greater than 100 microvolts) and all checkouts gave readable zero-offset values. In addition, there did not appear to be any significant change in dispersion from beginning to end of a data series. Amplifiers exhibiting these characteristics will be considered "Class I Stable."

Certain other amplifiers also had acceptably low noise-amplitude levels and no cases where checkouts could not be read, but the dispersion of the zero-offset sample averages was so great that a limited number of readings occurred off-scale. Amplifiers in this condition will be placed in the category "Class II Stable."

A third group comprises those remaining amplifiers whose noise-amplitude values were above the tolerance level, or for which zero-offset readings could not be made, or which gave large numbers of off-scale readings. Amplifiers exhibiting such faults will be termed "Unacceptable."

A set of decision rules, based on the above general principles, is summarized in Table 11 and may be used to diagnose the condition of any amplifier. These rules are to be applied after a suitable study period during which zero-offset samples and noise-amplitude readings are collected, and after data from a given amplifier have been analyzed. The analysis should include determination of the following: (a) percentage of noise-amplitude readings less than, or equal to, 20 millivolts, (b) presence of unreadable zero-offset checkouts, (c) percentage of off-scale zero-offset readings, and (d) sample-average standard deviation, $S_{\bar{x}}$. Except for this last factor, these values can usually be obtained from an inspection of a chart on which the zero-offset sample averages and the noise amplitude have been plotted as functions of time. The percentage levels and standard deviations specified in the rules of Table 11 have been chosen as a result of experience gained in the present study; in actual use it may be found that these criteria should be modified slightly.

Specific process controls have been suggested in Table 11 for each amplifier condition. The dispersion of the zero-offset sample averages from Class I Stable amplifiers is chosen small enough that standard control chart techniques can be used. It will be noted that the zero offset is to be readjusted to zero after each checkout. However, because the distribution of the zero-offset sample averages may not be normally distributed, even though the zero-offset is readjusted each time, a certain number of sample averages may fall outside the 3σ control limits. The process control specified for the Class II Stable amplifiers is based on the expected zero-offset drift. If a measure of the 90 per cent level of the three-day zero-offset drift can be made, and if it does not exceed 40 microvolts, a checkout and readjustment need be made only once every three days. It may be found, however, that some times the drift will exceed 40 microvolts in three days; in these cases daily checkouts are called for. Those amplifiers that are rated Unacceptable should be repaired or replaced if possible.

In order to diagnose an amplifier, it is suggested that a history of checkout data for a two-week period (ten workdays) be accumulated initially with samples of three zero-offset readings being taken twice a

Table 11. Diagnostic Decision Rules and Associated Process Controls for Operational Amplifiers

Condition	Decision Rules	Process Controls
Class I Stable	1. 95 per cent of noise-amplitude values $\leq$ 20 millivolts. 2. All checkouts give readable zero-offset values. 3. No zero-offset readings are off-scale. 4. Dispersion approximately constant. 5. $S_{\bar{x}} \leq 30$ microvolts.	1. Set control-chart limits $\pm 3S_{\bar{x}}$ from zero. 2. Readjust zero offset to zero after each sample. 3. Take three readings per sample. 4. Sample after the first operating hour every Monday. 5. If sample average is out of control, sample again the next day. 6. Repeat process 5 throughout week; if sample average continues to be out of control, then rediagnose.
Class II Stable	1. 95 per cent of noise-amplitude values $\leq$ 20 millivolts. 2. All checkouts give readable zero-offset values. 3. Several off-scale zero-offset readings, but no more than 20 per cent of total. 4. Dispersion approximately constant although generally large ($S_{\bar{x}} > 30$ microvolts).	1. Readjust zero offset to zero after each sample. 2. Take three readings per sample. 3. Sample after the first operating hour every Monday and Wednesday if three-day 90 per cent drift is less than 40 microvolts. 4. If the three-day sample-average drift is greater than 40 microvolts, check daily. Amplifiers with drifts greater than 90 microvolts per day are to be considered unacceptable.
Unacceptable	1. Noise-amplitude level > 20 millivolts. 2. Several checkouts are not readable. 3. Off-scale readings occur frequently.	1. No control limits or checkout program. 2. Repair or replace. 3. If circumstances force its use in this condition, such an amplifier should be used preceding integrators, and then should be checked both prior to and after use.

day (e.g., at 9 a.m. and 5 p.m.) during this period. Also, a single noise-amplitude reading should be recorded whenever a zero-offset sample is taken. This will provide 20 sample sets with which to estimate the process parameters. Each amplifier can then be categorized according to the decision rules in Table 11. On the basis of the observed data the suggested control techniques could be applied. Data from the succeeding checkout program could be accumulated and used to modify as well as monitor the process.

Two checkouts per day are suggested as a compromise between placing a burden on the analog computer facility by requiring additional checkouts in the middle of its daily operations or, on the other hand, by having the diagnostic period extended because only one reading per day was taken. Figure 16 presents zero-offset sample averages of data collected from an amplifier at 9 a.m., 1 p.m., and 5 p.m.; these plots (believed to be typical) indicate that the patterns of readings at 9 a.m. and 5 p.m. should adequately reflect the characteristics of readings which might be taken at other times during the day.

Once a history has been obtained for each amplifier and its condition has been diagnosed, it would probably be expedient to collect amplifiers of a similar type into groups, and assign these groups to common amplifier panels. Each panel could then have a checkout program of its own.

Checkout Program.--The applicability of the technique outlined in Table 11 to the data collected during this study may now be demonstrated. The long-term and three-week series were treated separately so that sixteen cases were considered. Table 12 gives the results of this application;

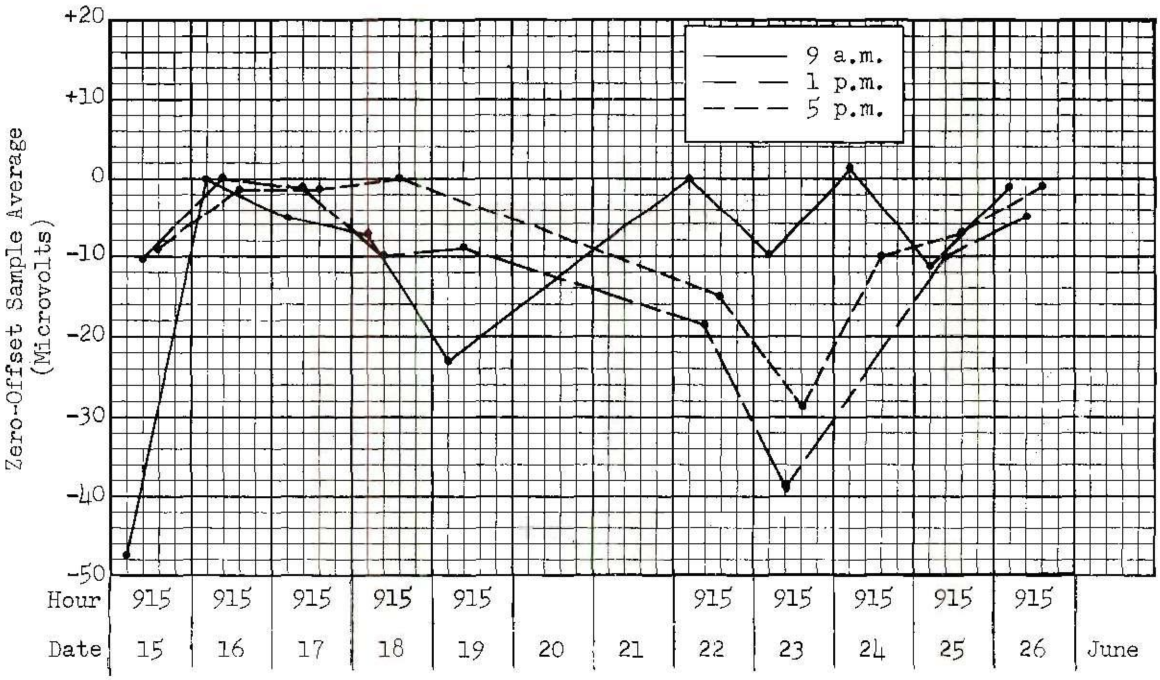


Figure 16. Plots of Zero-Offset Sample Averages According to the Time of Day: Part of Three-Week Data from Amplifier 12.

Table 12. Application of Decision Rules to Establish the Condition and Associated Process Controls for the Operational Amplifiers Under Study

Amplifier Condition	Amp.	Data Series[c]	Per Cent of Total Number: Noise Amplitude > 20 Millivolts	Per Cent of Total Number: Zero-Offset Samples, Unreadable	Per Cent of Total Number: Zero-Offset Samples, Off Scale	Zero-Offset Samples: Observed Dispersion[a] $S_{\bar{x}}$	Zero-Offset Samples: Control Level[a] $3S_{\bar{x}}$
Class I Stable	12	L.T.	0	0	9	28	84
		T.W.	0	0	0	11	33
	16	L.T.	0	0	0	20	60
	17	L.T.	0	0	2	20	60
		T.W.	0	0	0	18	54
	19	L.T.	4	0	0	16	48
		T.W.	0	0	0	17	51
Class II Stable	26	L.T.	2	0	20	44	-
		T.W.	0	0	3	54	-
Unacceptable	16[b]	T.W.	0	20	0	31	-
	21	L.T.	2	11	29	36	-
		T.W.	0	43	29	-	-
	29	L.T.	98	87	13	35	-
		T.W.	100	0	0	29	-
	30	L.T.	40	15	9	40	-
		T.W.	41	3	0	26	-

Notes: (a) Microvolts.
(b) The data summarized here are from 17 June on.
(c) L.T. = Long Term
T.W. = Two Week

the percentages shown are based on data from the various tables in Chapter III. The upper and lower control limits placed $\pm 3S_{\bar{x}}$ from zero provide satisfactory limits for the observed readjusted data (Figures 8, 9, 11, and 12); it is expected that they would serve equally as well with readjusted data from those amplifiers which were not readjusted during the present study. Unfortunately, only sketchy and inconclusive data are available on the zero-offset drift with a 3-day lag for Amplifier 26; Figure 13 provides data only for cases where intervening readjustments took place. The 90 per cent drift level for a lag of one day is so large that a daily readjustment would probably be required as a matter of course for Amplifier 26.

A comparison of Table 12 with Table 10 shows that the proposed decision rules produce results which are consistent with the opinions of the technician who maintained the equipment and who collected most of the data reported herein.

CHAPTER V

CONCLUSIONS

Operational amplifiers display such distinctive individual traits that no single control technique is feasible. There appears to be no direct functional relationship between a given noise-amplitude observation, a corresponding zero-offset reading, and the general condition of the amplifier in question, even though tolerance levels on these readings determine whether or not the amplifier is accepted as being in working order. It is the history of these parameters which provides a basis for prediction of amplifier performance during a subsequent time interval. In order to know whether a given amplifier will have acceptable noise-amplitude and zero-offset values throughout a given period, its performance parameters for a like previous period must be known.

Questions posed in the Introduction were concerned with several aspects of operational amplifiers, namely: (a) prediction of the drift rate of the zero offset, (b) frequency of readjustment of zero offset, (c) correlation between zero offset and noise amplitude, (d) effects of environmental factors, and (e) design of an optimal checkout program based on results of the present study. Discussions on each of these points have appeared in the previous two chapters and are summarized below.

(a) There is a marked tendency for the zero-offset process mean to drift; the drift rate and direction appear to be a function of the individual amplifier only. While environmental factors may affect this rate, the limited evidence available suggests that they simply contribute to the dispersion of values about the process mean. This drift can only be determined by examining zero-offset sample averages taken daily for a period of two or more weeks, where the zero-offset values are not readjusted to zero. For example, Figures 11a and 12a show a drift rate of about -1, -3, and -2 microvolts per day for Amplifiers 12, 17, and 29, respectively. The data shown in Figures 8a and 9a suggest that the process of readjustment may change the drift direction, though in general the rate remains sensibly constant. These latter data also suggest the possibility that the drift rate may change with the value of the zero-offset process mean. Therefore, while the drift of the process mean can be used to predict the general (statistical) performance of an amplifier which is not readjusted, and while the statistical performance of a readjusted amplifier can also be predicted, individual readings cannot be predicted except as being within the process-mean dispersion limits.

(b) Readjustment of the zero offset not only breaks up the drift pattern but also places the process mean near zero. Because there is a measurable drift and because it is advantageous to operate in the near-zero region, it appears desirable that the offset be readjusted to zero after each checkout.

(c) There does not appear to be any correlation between the noise-amplitude and the zero-offset readings taken at a given time. In addition, an amplifier may have an acceptable noise-amplitude history while having an unacceptable drift history, and *vice versa*.

(d) It has been shown that not-readjusted zero-offset readings do correlate with the room temperature over a period of about a day. This correlation becomes less marked with time so that it is not noticeable at the end of three weeks. No temperature correlation was detected in the readjusted data. Power-supply voltages did not correlate with zero-offset or noise-amplitude data in either case.

(e) A checkout program has been designed around a system for diagnosing the condition of each amplifier. This is based on the premise that the observed amplifier condition will change but little between checkouts, and that the checkouts will contribute to a progressively more complete picture of the amplifier's condition. Changes in the process are indicated when checkouts give readings outside established control limits. A periodic (e.g., every six months) re-evaluation of every amplifier's condition may be necessary. A suggested program is outlined in the previous chapter (see page 47).

CHAPTER VI

RECOMMENDATIONS

Because the results of this study are based upon a somewhat limited number of operational amplifiers, it is recommended that the checkout program outlined in Chapter IV be employed on a large scale by an analog computer facility for a period of at least one year. This should uncover possible undetected peculiarities in the performance of operational amplifiers as well as any unforeseen difficulties in applying the program. Specific efforts should be made to answer such questions as (a) whether or not the decision rules set forth herein are at the correct level, and (b) whether or not the control limits will detect a change in the process zero-offset level.

It is further recommended that an intensive study be performed, similar to the previously described three-week sequence but over a longer period of time and with the roles of the readjusted and not-readjusted amplifiers interchanged midway through the period. This comparative study should answer the question of whether or not readjustment affects the dispersion of the zero-offset sample averages.

It is also proposed that any continuing effort include an evaluation of computing errors caused by zero offset and noise in operational amplifiers. This problem could be investigated by setting up and testing a typical computer program (one for which the solution is accurately known) incorporating operational amplifiers whose conditions have been thoroughly studied.

Finally, it is suggested that the present zero-offset meter be replaced by an instrument with a scale which covers a more extended range. This improvement would permit more precise study of amplifier drift patterns which might well reveal characteristic frequency distributions of zero offset, either for amplifiers as a class or for individual units.

APPENDIX

DATA FROM PANEL 231*

Date	Amplifier 12 X	Amplifier 12 A	Amplifier 16 X	Amplifier 16 A	Amplifier 17 X	Amplifier 17 A	Amplifier 19 X	Amplifier 19 A	Power-Supply Volts	Room Temp. ^{o}C
Feb.	+ 55	3	+ 10	4	- 5	3	- 10	10		
10	+ 60		+ 5		0		- 10			
	+ 55		+ 5		- 5		- 10			
11	+ 35	4	- 5	3	- 5	4	0	9		
	+ 30		0		0		+ 5			
	+ 35		- 5		- 5		+ 10			
12	+ 5	4	+ 5	4	- 5	6	0	9		
	+ 5		- 5		- 5		+ 5			
	0		- 10		- 5		+ 5			
14	+ 75	3	-	3	+ 5	5	+ 10	9		
	+ 75		- 5		0		+ 10			
	+ 70		- 10		0		+ 10			
16	+ 10	4	- 10	4	0	6	+ 20	8		
	+ 5		- 10		0		+ 20			
	+ 5		- 10		+ 5		+ 10			
17	+ 55	5	- 5	4	+ 5	7	+ 10	9		
	+ 50		- 30		+ 5		+ 5			
	+ 45		- 10		+ 5		+ 10			
18	>+100	3	- 15	3	- 5	5	- 10	8		
	>+100		- 15		- 5		- 5			
	>+100		- 20		- 5		- 10			
23	- 60	3	- 50	3	- 30	5	- 25	8	-250	
	- 60		- 45		- 30		- 20		+250	
	- 70		- 55		- 30		- 20			
24	- 90	3	- 45	3	- 20	5	- 20	10	-249.8	
	- 90		- 50		+ 50		- 20		+250.6	
	- 75		- 50		- 30		- 20			
25	- 90	4	- 10	3	- 25	6	- 10	8	-250.2	
	- 90		- 5		- 30		- 5		+250.4	
	-100		-		- 35		- 5			
26	- 95	4	+ 10	3	- 30	6	- 10	10	-250.0	
	- 90		+ 10		- 45		- 10		+250.4	
	- 90		+ 5		- 25		- 10			

*X = Zero-Offset Readings in Microvolts.
A = Noise Amplitude in Millivolts.

PANEL 231 (Cont.)

Date	Amplifier 12 X	Amplifier 12 A	Amplifier 16 X	Amplifier 16 A	Amplifier 17 X	Amplifier 17 A	Amplifier 19 X	Amplifier 19 A	Power-Supply Volts	Room Temp. °C
Feb.	- 90	4	0	4	- 40	7	- 15	8	-249.8	
27	- 95		+ 5		- 25		- 10		+250.5	
	- 90		+ 10		- 40		- 10			
Mar.	-100	4	+ 40	4	- 35	6	- 15	8	-250.0	
5	-100		+ 45		- 35		- 25		+250.3	
	<-100		+ 25		- 15		- 15			
9	- 90	4	- 25	4	- 15	6	- 25	8	-250.1	
	-100		0		- 40		- 15		+250.4	
	-100		0		- 50		- 25			
10	- 60	4	0	5	- 25	6	- 5	100	-250.0	
	- 65		- 5		- 25		- 5		+250.3	
	- 90		- 10		- 10		- 5			
11	- 90	5	0	5	- 20	7	- 25	8	-250.1	
	-100		0		- 15		- 10		+250.4	
	-100		- 5		- 10		- 10			
12	- 65	5	0	5	- 15	7	- 10	8	-250.2	
	- 75		+ 5		- 40		- 10		+250.4	
	- 75		+ 10		- 15		- 10			
13	- 50	4	- 40	4	- 30	5	- 45	8	-250.1	
	- 50		- 40		- 50		- 45		+250.2	
	- 50		- 40		- 50		- 55			
19	- 45	5	- 20	6	- 15	6	- 15	200	-250.0	
	- 50		- 30		- 10		- 25		+250.4	
	- 45		- 35		- 20		- 20			
20	- 40	4	- 15	4	- 5	6	- 25	490	-246.4	
	- 45		- 15		- 15		- 30		+250.2	
	- 50		- 15		- 25		- 25			
21	- 40	4	+ 10	4	- 20	6	+ 5	10	-249.2	
	- 45		+ 10		- 30		0		+250.1	
	- 30		+ 10		- 30		0			
23	- 35	3	+ 20	3	- 10	6	+ 15	10	-250.1	
	- 45		+ 25		- 10		+ 10		+250.6	
	- 45		+ 25		- 15		+ 15			
24	- 50	4	+ 15	3	- 15	6	+ 5	10	-250.2	
	- 50		+ 20		- 10		+ 10		+251.1	
	- 45		+ 20		0		+ 10			

PANEL 231 (Cont.)

Date	Amplifier 12 X	A	Amplifier 16 X	A	Amplifier 17 X	A	Amplifier 19 X	A	Power-Supply Volts	Room Temp. °C
Mar. 25	- 40	3	0	3	- 10	6	+ 5	11	-250.2	
	- 45		+ 5		- 10		+ 10		+250.6	
	- 50		0		- 15		+ 5			
26	- 45	3	- 10	3	- 20	6	- 5	10	-250.1	
	- 50		- 10		- 20		- 5		+250.6	
	- 45		- 5		- 25		0			
27	- 55	3	- 10	3	- 30	6	- 5	10	-250.1	
	- 55		- 10		- 30		0		+250.6	
	- 50		- 15		- 25		+ 5			
30	- 60	3	+ 5	3	- 35	6	0	10	-250.1	
	- 65		- 15		- 35		- 5		+250.6	
	- 60		- 15		- 35		0			
Apr. 1	- 55	3	+ 5	3	- 10	6	+ 10	10	-249.8	
	- 55		+ 5		- 55		+ 10		+250.3	
	- 50		+ 5		- 10		- 10			
3	- 90	3	- 15	3	- 55	6	- 15	10	-249.9	
	- 90		- 15		- 80		- 10		+250.2	
	-100		- 10		- 75		- 10			
6	- 80	3	+ 15	3	- 65	6	- 5	11	-249.8	
	- 85		+ 10		- 70		0		+250.2	
	- 90		+ 10		- 60		0			
7	- 55	3	0	3	- 20	6	+ 5	17	-249.7	
	- 90		+ 5		- 50		+ 5		+250.2	
	- 85		+ 5		- 55		+ 5			
8	-100	5	+ 10	5	- 60	7	0	10	-249.8	
	-105		+ 5		- 65		- 5		+250.2	
	-105		0		- 65		0			
9	<-100	3	- 45	3	<-100	6	- 50	11	-249.8	28.5
	<-100		- 45		<-100		- 45		+250.1	
	<-100		- 50		<-100		- 45			
22	0	3	- 5	3	0	6	- 5	10	-250.0	23.2
	0		-		- 5		- 5		+250.6	
	0		-		- 5		- 5			
24	0	7	- 5	5	0	7	- 5	10	-250.0	25.6
	0		0		- 5		0		+250.5	
	0		- 5		- 10		- 10			

PANEL 231 (Cont.)

Date	Amplifier 12 X	A	Amplifier 16 X	A	Amplifier 17 X	A	Amplifier 19 X	A	Power-Supply Volts	Room Temp. $^{\circ}C$
May	+ 10	6	0	6	+ 10	7	+ 5	10	-250.0	29.8
1	+ 40		+ 5		+ 15		0		+250.5	
	+ 40		+ 5		+ 5		0			
6	- 5	5	- 10	5	+ 30	7	- 10	11	-249.6	29.8
	+ 5		+ 5		+ 15		- 10		+250.4	
	+ 5		0		+ 20		- 40			
8	0	5	0	5	+ 10	7	+ 10	10	-249.7	27.0
	+ 5		0		+ 10		+ 5		+250.4	
	0		- 10		+ 25		+ 10			
12	+ 5	6	- 5	6					-249.8	28.0
(9am)	0		0						+250.6	
	+ 5		- 5							
(10am)	0	5	- 5	5					-249.8	27.4
	- 5		- 10						+250.4	
	0		- 5							
(11am)	- 5	5	- 10	5					-249.8	26.6
	0		- 10						+250.6	
	- 5		- 10							
(12n)	- 5	5	- 5	5					-249.8	26.7
	- 5		- 5						+250.4	
	- 5		- 5							
(1pm)	0	5	0	5					-249.8	27.0
	- 5		+ 10						+250.4	
	- 5		- 10							
(2pm)	0	4	+ 5	4					-249.8	27.9
	0		- 5						+250.2	
	- 5		0							
(3pm)	0	4	- 5	4					-249.8	28.0
	0		- 5						+250.3	
	0		- 5							
(4pm)	0	4	- 10	4					-249.8	28.2
	+ 5		- 5						+250.3	
	0		- 5							
(5pm)	- 5	4	- 10	4					-249.8	28.2
	+ 5		- 5						+250.2	
	+ 5		- 10							
13	- 10	4	- 10	5					-249.9	25.8
(9am)	- 10		- 10						+250.5	
	- 5		- 10							

PANEL 231 (Cont.)

Date	Amplifier 12		Amplifier 16		Amplifier 17		Amplifier 19		Power-Supply Volts	Room Temp. °C
	X	A	X	A	X	A	X	A		
May	0	6	- 25	6					-249.9	26.3
13	- 5		- 15						+250.4	
(10am)	- 5		- 20							
(11am)	- 5	5	- 10	5					-249.9	26.9
	0		- 25						+250.2	
	- 5		- 15							
(12n)	- 5	5	- 30	4					-249.6	27.2
	- 5		- 25						+250.3	
	- 5		- 30							
(1pm)	0	5	- 10	4					-249.6	27.5
	+ 5		0						+250.2	
	+ 5		- 10							
(2pm)	+ 5	5	- 5	4					-249.6	27.9
	+ 10		- 5						+250.2	
	+ 5		- 10							
(3pm)	+ 10	6	- 20	6	+ 10	7	+ 10	9	-249.6	28.0
	+ 10		- 25		+ 10		+ 5		+250.2	
	+ 5		- 20		+ 10		+ 10			
(4pm)	+ 25	6	- 10	6					-249.6	28.5
	+ 25		- 10						+250.1	
	+ 15		- 10							
(5pm)	+ 25	6	0	5					-249.6	28.9
	+ 25		0						+250.1	
	+ 15		- 10							
14	0	5	- 25	4					-249.9	29.2
(9am)	+ 5		- 10						+250.5	
	+ 5		- 5							
(10am)	0	5	- 15	4					-249.8	24.7
	0		- 10						+250.6	
	0		- 10							
(11am)	0	5	- 10	5					-249.8	25.3
	- 5		- 25						+250.5	
	+ 5		- 5							
(12n)	+ 5	5	- 10	5					-249.8	25.9
	+ 5		- 10						+250.4	
	0		- 10							
(1pm)	+ 10	5	- 10	5					-249.8	25.9
	+ 10		- 15						+250.4	
	+ 10		- 25							

PANEL 231 (Cont.)

Date	Amplifier 12 X	A	Amplifier 16 X	A	Amplifier 17 X	A	Amplifier 19 X	A	Power-Supply Volts	Room Temp. °C
May 14 (2pm)	+ 20 + 10 + 25	4	- 10 - 15 - 10	4					-249.8 +250.4	25.9
(3pm)	+ 25 + 10 + 25	5	- 20 - 15 - 10	4	+ 20 + 40 + 10	6	+ 10 + 10 + 25	8	-249.7 +250.3	26.1
(4pm)	+ 15 + 25 + 20	5	- 10 - 10 - 15	4					-249.7 +250.2	26.4
May 15	- 20 - 15 - 25	5	- 60 - 50 - 50	4	- 20 - 25 - 30	6	- 25 - 30 - 20	10	-249.6 +250.0	27.1
20	- 5 - 5 - 5	5	- 25 - 15 - 10	4	+ 15 - 5 - 15	7	- 50 - 40 - 40	14	-249.8 +250.2	26.9
21	- 15 - 25 - 15	4	- 10 - 25 - 25	4	- 5 - 5 - 5	7	- 50 - 40 - 50	15	-249.6 +250.1	29.4
22	- 30 - 40 - 30	4	- 20 - 15 - 15	4	0 0 - 25	6	- 20 - 20 - 10	13	-249.8 +250.2	27.8
26	- 65 - 70 - 70	5	- 55 - 45 - 40	5	- 30 - 25 - 25	7	- 10 0 0	15	-249.9 +250.4	26.9
27	- 40 - 50 - 45	6	- 25 - 25 - 25	5	- 40 - 40 - 25	6	- 35 - 10 - 15	11	-250.0 +250.6	25.3
Jun. 4	- 50 - 70 - 50	4	- 40 - 45 -100	5	- 30 - 45 - 45	3	0 0 0	12	-249.9 +250.4	25.0
5	- 50 - 60 - 60	-	- 30 - 30 - 45	-	- 45 - 55 - 50	-	+ 25 + 20 + 25	-	-249.9 +250.6	24.4
15 (9am)	- 50 - 45 - 45	3	- 45 - 50 - 45	3	- 65 - 50 - 55	7	+ 15 + 10 + 15	10	-250.2 +251.2	22.4

PANEL 231 (Cont.)

Date	Amplifier 12 X	A	Amplifier 16 X	A	Amplifier 17 X	A	Amplifier 19 X	A	Power-Supply Volts	Room Temp. °C
Jun.	- 10	4	0	4	- 15	7	+ 35	10	-250.1	24.1
15	- 5		0		- 15		+ 45		+250.9	
(2pm)	- 15		- 10		- 15		+ 40			
(5pm)	- 10	4	+ 10	4	- 25	7	+ 45	12	-250.0	25.0
	- 15		+ 10		- 15		+ 30		+250.7	
	0		+ 10		- 15		+ 45			
16	0	5	+ 25	4	- 10	7	+ 50	11	-250.2	22.3
(9am)	0		+ 35		- 10		+ 70		+251.2	
	0		+ 40		- 10		+ 55			
(1pm)	0	4	+ 15	4	- 15	7	+ 50	14	-250.1	24.0
	0		+ 10		- 15		+ 45		+250.9	
	0		+ 10		- 10		+ 45			
(5pm)	0	5	+ 10	5	- 15	7	+ 45	13	-250.1	23.0
	0		+ 10		- 15		+ 45		+251.0	
	- 5		+ 15		- 15		+ 30			
17	- 5	5	0	5	- 20	7	0	10	-250.2	22.7
(9pm)	- 5		+ 5		- 15		0		+251.1	
	- 5		0		- 20		- 10			
(2pm)	0	5	0	5	- 25	7	- 15	10	-250.0	22.5
	- 5		0		- 20		- 5		+250.9	
	0		+ 5		- 20		- 10			
(5pm)	- 5	5	-	7	- 20	7	- 10	10	-250.0	23.0
	+ 5		-		- 25		- 5		+250.8	
	- 5		-		- 35		- 10			
18	- 10	5	0	5	- 30	8	+ 10	11	-249.9	22.5
(9am)	- 5		+ 10		- 15		+ 5		+251.0	
	- 5		+ 10		- 20		+ 10			
(1pm)	- 10	5	0	5	0	8	0	12	-250.0	24.9
	- 10		0		- 15		0		+250.8	
	- 10		0		- 15		0			
(5pm)	0	5	+ 5	5	- 25	7	0	9	-250.0	23.8
	0		0		- 20		0		+250.8	
	0		+ 10		- 25		0			
19	- 25	4	- 15	4	- 25	6	0	10	-249.9	21.9
(9am)	- 15		- 10		- 25		- 5		+251.0	
	- 30		- 20		- 20		+ 10			
(1pm)	- 10	4	0	4	- 15	7	+ 5	12	-250.0	23.7
	- 10		0		- 30		+ 5		+250.9	
	- 5		0		- 20		0			

PANEL 231 (Cont.)

Date	Amplifier 12 X	A	Amplifier 16 X	A	Amplifier 17 X	A	Amplifier 19 X	A	Power-Supply Volts	Room Temp. °C
Jun.	0	4	+ 5	4	- 5	6	+ 10	16	-249.6	28.5
22	0		+ 10		- 10		+ 25		+250.4	
(9am)	0		- 5		+ 5		+ 15			
(1pm)	- 15	4	-	4	- 20	7	- 15	12	-250.2	24.5
	- 20		-		- 35		- 15		+251.3	
	- 20		-		- 40		- 15			
(5pm)	- 20	4	- 15	4	- 50	7	- 15	12	-250.2	24.0
	- 15		0		- 40		- 5		+251.0	
	- 10		0		- 45		- 15			
23	- 5	4	- 15	4	- 20	7	0	12	-250.2	29.5
(9am)	- 10		- 10		- 25		+ 5		+250.8	
	- 15		- 15		- 20		0			
(1pm)	- 30	4	-	5	- 50	7	- 25	11	-250.1	23.5
	- 45		-		- 55		- 15		+251.0	
	- 40		-		- 50		- 15			
(5pm)	- 30	4	+ 15	4	- 55	7	- 20	12	-250.2	23.5
	- 30		+ 25		- 50		- 20		+251.0	
	- 25		+ 20		- 55		- 15			
24	+ 5	4	+ 20	4	- 45	7	+ 30	11	-250.0	28.0
(9am)	0		+ 35		- 40		+ 25		+251.0	
	0		+ 25		- 40		+ 10			
(4pm)	- 10	4	+ 25	4	- 35	7	+ 10	11	-250.2	23.0
	- 10		+ 25		- 45		+ 15		+251.0	
	- 10		+ 35		- 35		+ 10			
25	- 10	4	+ 25	4	- 40	7	+ 20	11	-250.2	22.0
(10am)	- 15		+ 30		- 45		+ 20		+251.0	
	- 10		+ 40		- 40		+ 15			
(1pm)	- 10	4	-	4	- 45	7	0	11	-250.2	23.0
	- 10		-		- 30		0		+250.9	
	- 10		-		- 35		0			
(5pm)	- 5	4	0	4	- 25	7	0	8	-250.1	24.0
	- 10		0		- 40		- 5		+250.9	
	- 5		- 20		- 45		0			
26	- 5	4	+ 80	4	- 50	7	+ 35	8	-250.2	24.0
(9am)	0		+ 75		- 45		+ 30		+250.9	
	0		+ 75		- 45		+ 25			
(1pm)	- 5	4	+ 50	4	- 65	7	+ 25	9	-250.1	24.5
	- 5		+ 60		- 40		+ 15		+250.8	
	- 5		+ 55		- 50		+ 20			

PANEL 231 (Cont.)

Date	Amplifier 12 X	Amplifier 12 A	Amplifier 16 X	Amplifier 16 A	Amplifier 17 X	Amplifier 17 A	Amplifier 19 X	Amplifier 19 A	Power-Supply Volts	Room Temp. °C
Jun. 26 (5pm)	0 0 - 5	4	+ 25 + 20 + 20	4	- 55 - 55 - 50	7	- 5 - 10 - 5	8	-250.1 +250.9	25.0
30 (1pm)	- 20 - 15 - 15	3	- 45 - 45 - 30	3	- 60 - 55 - 75	7	+ 10 - 5 0	10	-250.0 +250.8	24.7
(5pm)	- 15 - 25 - 40	4	+ 5 + 25 + 20	4	- 65 - 50 - 55	7	- 5 - 10 + 5	10	-250.0 +251.0	23.0
Jul. 1 (10am)	- 10 - 20 - 25	5	- 50 - 60 - 60	5	- 60 - 65 - 75	7	+ 5 0 0	16	-250.0 +250.8	25.0
(1pm)	- 15 - 25 - 25	5	- 45 - 50 - 50	5	- 70 - 65 - 65	7	0 0 - 10	10	-250.0 +250.8	24.4
(5pm)	- 10 - 15 - 25	5	- - -	5	- 55 - 55 - 55	7	+ 5 + 5 + 10	13	-250.0 +250.9	25.1
2 (9am)	- 10 - 10 - 10	5	- - -	5	- 40 - 40 - 40	7	+ 20 + 30 + 40	12	-250.2 +251.0	22.6
(5pm)	- 10 - 10 - 10	5	+ 30 - + 15	5	- 55 - 60 - 50	7	0 - 5 - 5	11	-250.0 +250.8	23.9

DATA FROM PANEL 239*

Date	Amplifier 21 X	Amplifier 21 A	Amplifier 26 X	Amplifier 26 A	Amplifier 29 X	Amplifier 29 A	Amplifier 30 X	Amplifier 30 A	Power-Supply Volts	Room Temp. °C
Feb.	- 10	4	+ 15	9	- 10	60	- 40	10		
10	0		0		- 5		- 35			
	- 5		+ 10		- 10		- 25			
11	- 10	5	- 20	9	- 15	70	- 10	11		
	- 10		- 15		- 20		- 15			
	- 10		- 10		- 20		- 10			
12	- 20	6	- 25	11	- 25	80	- 15	13		
	- 10		- 25		- 20		- 15			
	- 15		- 25		- 20		- 15			
14	- 15	5	- 40	10	- 45	90	- 10	110		
	- 25		- 35		- 50		- 15			
	- 30		- 40		- 40		- 10			
16	- 10	5	- 60	10	- 55	80	- 30	160		
	- 10		- 60		- 55		- 40			
	+ 15		- 70		- 60		- 45			
17	+100	8	>+100	10	+ 40	75	+ 55	150		
	>+100		>+100		+ 25		+ 50			
	>+100		>+100		+ 25		+ 55			
18	+100	5	- 25	10	+ 40	80	- 30	115	+ 0.8	
	+100		- 30		+ 35		- 50			
	+100		- 30		+ 20		- 45			
23	0	5	- 5	9	+ 5	95	-	160	-250	
	- 25		- 15		- 25		-		+250	
	- 25		- 10		- 25		-			
24	<-100	5	- 10	9	- 25	60	-	160	-250	
	<-100		- 30		- 10		-		+250	
	<-100		- 10		- 10		-			
25	-	5	0	9	- 15	70	-	150	-250.0	
	-		0		- 10		-		+249.9	
	-		- 5		- 10		-			

*X = Zero-Offset Readings in Microvolts.
A = Noise Amplitude in Millivolts.

PANEL 239 (Cont.)

Date	Amplifier 21 X	A	Amplifier 26 X	A	Amplifier 29 X	A	Amplifier 30 X	A	Power-Supply Volts	Room Temp. °C
Feb. 26	- 20 - 5 + 40	5	+ 10 + 40 + 10	10	- 10 - 10 - 15	110	- - -	150	-249.8 +249.7	
27	+ 40 + 10 + 15	5	- 15 - 25 - 40	10	- 15 - 50 - 30	100	- - -	120	-249.6 +249.6	
Mar. 5	- 55 - 50 - 55	5	-100 -100 -100	9	- 80 - 90 - 75	75	- 55 - 55 - 50	13	-249.8 +249.8	
9	- 50 - 55 - 60	6	-100 <-100 <-100	10	<-100 <-100 <-100	80	- 30 - 25 - 25	90	-249.8 +249.8	
10	<-100 <-100 <-100	5	- 90 - 75 - 90	10	<-100 <-100 <-100	80	- 90 - 90 - 90	85	-249.7 +249.8	
11	<-100 <-100 <-100	5	- 75 - 65 - 75	10	<-100 <-100 <-100	80	<-100 <-100 <-100	13	-249.8 +249.8	
12	<-100 <-100 <-100	6	-100 <-100 <-100	10	<-100 <-100 <-100	90	<-100 - 90 - 85	13	-249.8 +249.8	
13	+ 25 + 10 + 20	5	+ 30 + 20 + 25	10	+ 20 + 10 + 25	80	- 40 - 40 - 40	13	-249.8 +250.1	
19	- 5 - 5 -	6	+ 10 + 5 - 5	10	- 10 - 10 - 10	100	- 30 - 40 - 45	60	-249.8 +249.8	
20	+ 30 + 30 + 25	6	+ 30 + 30 + 30	11	+ 20 + 15 + 25	75	+ 60 + 50 + 60	13	-249.6 +249.8	
23	0 - 10 + 5	6	- 15 - 15 - 10	15	- 10 0 0	75	+ 35 + 25 + 25	12	-249.8 +249.8	
24	- 30 - 25 - 25	6	- 35 - 40 - 30	11	- 25 - 30 - 25	70	- 10 - 5 - 10	12	-249.0 +250.0	

PANEL 239 (Cont.)

	Amplifier 21		Amplifier 26		Amplifier 29		Amplifier 30		Power-Supply	Room Temp.
Date	X	A	X	A	X	A	X	A	Volts	°C
Mar.	- 20	6	- 25	13	- 25	85	- 15	16	-250.0	
25	- 15		- 25		- 20		- 15		+250.2	
	- 20		- 20		- 20		- 10			
26	- 30	6	+ 50	11	- 20	85	+ 30	10	-249.9	
	- 15		+ 40		0		+ 15		+250.0	
	- 10		+ 35		0		+ 15			
27	- 35	6	+ 30	17	- 25	75	- 20	13	-249.9	
	- 25		+ 40		- 25		- 15		+250.0	
	- 20		+ 15		- 15		- 15			
30	- 15	7	- 5	11	- 40	80	+ 5	13	-249.8	
	- 5		- 5		- 25		+ 15		+250.0	
	0		- 20		- 25		+ 10			
Apr.	+ 40	6	+ 40	10	+ 10	100	- 5	13	-249.7	
1	+ 5		+ 40		+ 5		- 5		+249.8	
	+ 10		+ 30		+ 10		- 10			
3	+ 55	6	>+100	10	+ 60	120	+ 50	15	-249.8	
	+ 60		>+100		+ 75		+ 75		+249.9	
	+ 50		>+100		+ 75		+ 50			
6	>+100	5	- 20	10	>+100	125	+ 40	17	-249.7	
	>+100		- 15		+ 60		+ 10		+249.9	
	>+100		- 30		+100		+ 20			
7	-	6	- 15	10	+ 45	100	-	18	-249.6	
	-		- 70		+ 75		-		+249.9	
	-		- 45		+ 90		-			
8	+ 50	7	- 50	10	-	90	-	35	-249.8	
	+ 40		- 40		-		-		+249.9	
	-		- 45		-		-			
9	>+100	5	+ 70	9	+ 65	80	+100	12	-249.8	28.5
	>+100		+ 80		+ 50		+100		+249.9	
	>+100		+ 90		+ 75		>+100			
22	-	4	+ 75	9	+100	10	+ 55	13	-250.0	23.2
	-		+ 90		+100		+ 70		+250.3	
	-		+ 40		+100		+ 55			
24	+ 90	4	+ 75	9	+ 80	90	+ 35	21	-250.0	25.6
	-		+ 50		+ 80		+ 40		+250.2	
	-		+ 60		+ 85		+ 45			

PANEL 239 (Cont.)

Date	Amplifier 21 X	Amplifier 21 A	Amplifier 26 X	Amplifier 26 A	Amplifier 29 X	Amplifier 29 A	Amplifier 30 X	Amplifier 30 A	Power-Supply Volts	Room Temp. °C
May 1	+100	140	- 20	130	>+100	100	- 90	31	-249.8	29.8
	+ 50		- 15		>+100		- 90		+250.0	
	+ 60		- 45		>+100		<-100			
6	>+100	3	>+100	8	-	160	+ 55	12	-249.5	29.8
	>+100		>+100		-		+ 60		+249.8	
	>+100		>+100		-		+ 60			
8	- 25	4	<-100	9	-	160	- 5	8	-249.8	27.0
	- 10		- 70		-		+ 5		+249.9	
	- 10		-100		-		0			
13	-	5	>+100	10	-	300	+ 60	11	-249.8	28.0
	-		+100		-		+ 95		+249.8	
	-		+ 90		-		+ 75			
14	+100	4	+ 40	9	-	150	+ 40	13	-250.0	29.1
	+ 50		+ 50		-		+ 45		+250.0	
	+ 45		+ 40		-		+ 30			
15	>+100	5	>+100	11	-	130	+ 55	13	-249.9	27.1
	>+100		>+100		-		+ 50		+250.0	
	+ 90		>+100		-		+ 55			
20	- 55	5	- 25	10	+ 5	130	0	13	-250.0	26.9
	- 90		- 5		+ 10		0		+250.0	
	-100		- 5		+ 10		0			
21	<-100	5	+ 70	10	+ 40	130	+ 40	35	-249.8	29.4
	<-100		+ 60		+ 50		+ 40		+249.8	
	<-100		+ 50		+ 40		+ 40			
22	<-100	5	- 50	10	+ 25	150	- 10	35	-249.9	27.8
	<-100		- 65		+ 25		- 15		+250.0	
	<-100		- 70		+ 30		- 10			
26	<-100	5	<-100	10	+ 20	125	- 20	16	-249.9	26.9
	<-100		-100		+ 15		- 30		+250.2	
	<-100		<-100		+ 15		- 20			
27	<-100	4	+ 40	19	+ 50	100	+ 15	160	-250.0	25.3
	<-100		+ 20		+ 60		+ 10		+250.0	
	<-100		+ 30		+ 60		+ 10			
Jun. 4	<-100	5	+ 70	11	+ 70	110	+ 35	13	-249.6	25.0
	<-100		+ 60		+ 75		+ 30		+250.3	
	<-100		+ 50		+ 75		+ 25			

PANEL 239 (Cont.)

Date	Amplifier 21 X	A	Amplifier 26 X	A	Amplifier 29 X	A	Amplifier 30 X	A	Power-Supply Volts	Room Temp. °C
Jun.	<-100	5	- 20	11	+100	150	+ 10	15	-249.9	22.4
15	<-100		- 40		+100		+ 20		+250.2	
(9am)	<-100		- 50		+100		+ 10			
(2pm)	-	5	+ 50	11	- 10	130	+ 25	15	-250.2	24.1
	-		+ 50		- 5		+ 25		+250.2	
	-		-		- 10		+ 25			
(5pm)	>+100	5	+ 90	10	0	120	+ 30	15	-250.0	25.0
	>+100		+ 60		0		+ 25		+250.1	
	>+100		+ 70		0		+ 30			
16	- 25	5	- 5	11	- 5	120	- 5	15	-250.2	22.3
	-		- 50		+ 5		- 5		+250.3	
	-		- 15		- 5		- 5			
(1pm)	-	5	+ 45	11	- 5	280	+ 5	14	-250.0	24.0
	-		+ 30		- 5		+ 5		+250.1	
	-		+ 25		0		0			
(5pm)	-	5	+ 70	12	- 10	140	+ 25	15	-250.1	23.0
	-		+ 75		- 15		+ 20		+250.2	
	-		+ 90		- 10		+ 10			
17	-	5	-100	12	- 25	150	- 15	15	-250.0	22.7
(9am)	-		-100		- 10		- 10		+250.1	
	-		-100		0		- 10			
(2pm)	+100	6	+ 55	12	- 5	130	+ 45	15	-250.1	22.5
	-		+ 70		- 10		+ 25			
	-		+ 50		- 5		+ 25			
(5pm)	>+100	6	>+100	12	+ 25	120	+ 90	15	-250.0	23.0
	>+100		+100		+ 35		+ 90		+250.2	
	>+100		+100		+ 35		+ 85			
18	+ 50	6	0	12	+ 25	130	+ 15	15	-249.9	22.5
(9am)	-		+ 5		+ 20		+ 15		+250.2	
	+ 50		0		+ 20		+ 15			
(1pm)	-	6	+ 45	12	0	140	+ 25	100	-250.1	24.9
	-		+ 5		+ 25		+ 10		+250.0	
	-		+ 5		- 5		+ 10			
(5pm)	-	5	+100	12	+ 25	120	+ 50	150	-250.0	23.8
	-		+100		+ 25		+ 50		+250.0	
	-		+100		+ 10		+ 50			

PANEL 239 (Cont.)

Date	Amplifier 21 X	A	Amplifier 26 X	A	Amplifier 29 X	A	Amplifier 30 X	A	Power-Supply Volts	Room Temp. ^{o}C
Jun.	-	5	-100	10	+ 5	120	- 45	13	-250.0	21.9
19	-		-100		+ 5		- 45		+249.9	
(9am)	-		-100		+ 15		- 40			
(1pm)	-	5	+ 50	11	+ 10	130	+ 5	30	-249.8	23.7
	-		+ 35		+ 5		+ 10		+250.0	
	-		+ 50		+ 5		+ 5			
22	-	5	- 15	12	+ 15	110	- 5	30	-249.8	28.5
(9am)	-		- 10		+ 15		0		+250.0	
	-		- 20		+ 20		0			
(1pm)	-	5	+ 40	12	+ 5	110	+ 5	22	-250.2	24.5
	-		+ 15		+ 10		+ 10		+250.2	
	-		+ 25		+ 5		+ 20			
(5pm)	-	5	+ 15	12	+ 10	120	- 20	16	-250.0	24.0
	-		+ 40		0		+ 5		+250.0	
	-		+ 25		+ 5		0			
23	+ 10	5	- 50	17	+ 10	110	- 35	180	-250.2	29.5
(9am)	-		- 45		+ 20		- 35		+250.3	
	-		- 45		+ 15		- 35			
(1pm)	-	5	+ 25	11	+ 10	130	+ 25	180	-250.1	23.5
	-		+ 25		+ 10		-		+250.2	
	-		+ 25		+ 5		-			
(5pm)	>+100	5	+ 50	12	+ 10	140	-	180	-250.3	23.5
	>+100		+ 60		0		-		+250.4	
	>+100		+ 60		0		-			
24	0	5	0	12	+ 10	130	- 5	80	-250.2	28.0
(9am)	- 10		- 5		+ 5		0		+250.4	
	+ 5		- 40		+ 5		0			
(4pm)	-	5	+ 60	11	0	110	+ 30	130	-250.3	23.0
	-		+ 60		0		+ 35		+250.4	
	-		+ 50		0		+ 40			
25	-	5	0	12	0	110	- 15	240	-250.1	22.0
(10am)	-		- 15		- 15		- 20		+250.2	
	-		- 20		+ 5		- 20			
(1pm)	-	5	+ 5	12	+ 10	130	+ 10	250	-250.0	23.0
	-		+ 20		+ 15		+ 10		+250.0	
	-		+ 30		+ 5		+ 15			

PANEL 239 (Cont.)

Date	Amplifier 21 X	A	Amplifier 26 X	A	Amplifier 29 X	A	Amplifier 30 X	A	Power-Supply Volts	Room Temp. °C
Jun.	>+100	5	+ 40	12	0	120	+ 20	220	-250.0	24.0
25	>+100		+ 40		0		+ 25		+250.0	
(5pm)	>+100		+ 25		0		+ 30			
26	-	5	- 55	11	+ 20	140	- 5	70	-250.3	24.0
(9am)	-		- 50		+ 20		- 5		+250.4	
	-		- 55		+ 10		- 5			
(1pm)	-	5	- 30	12	+ 5	100	0	80	-250.2	24.5
	-		- 10		+ 10		- 5		+250.3	
	-		- 20		+ 10		0			
(5pm)	-	5	+ 35	11	0	110	+ 10	80	-250.2	25.0
	-		+ 45		0		+ 10		+250.2	
	-		+ 25		+ 10		+ 20			
30	-	5	- 25	11	- 20	150	- 25	150	-250.2	24.7
(1pm)	-		- 10		- 10		- 40		+250.2	
	-		- 10		- 10		- 30			
(5pm)	>+100	7	+ 40	12	- 15	125	+ 25	150	-250.2	23.0
	>+100		+ 40		- 10		+ 10		+250.4	
	>+100		+ 25		- 10		+ 15			
Jul.	>+100	6	- 55	12	- 10	130	0	150	-250.1	25.0
1	>+100		- 90		- 15		- 15		+250.2	
(10am)	>+100		- 80		- 10		- 10			
(1pm)	>+100	6	- 60	12	- 10	100	+ 15	130	-250.1	24.4
	>+100		- 55		0		+ 15		+250.2	
	>+100		- 25		0		+ 15			
(5pm)	>+100	6	+ 25	12	- 10	100	+ 10	150	-250.0	25.1
	>+100		+ 25		- 15		+ 10		+250.2	
	>+100		+ 20		- 5		+ 10			
2	-	6	-100	12	- 10	120	- 45	16	-250.1	22.6
(9am)	-		- 95		- 5		- 45		+250.3	
	-		-100		- 5		- 40			
(5pm)	>+100	6	+ 80	12	0	110	+ 45	15	-250.1	23.9
	>+100		+100		- 5		+ 15		+250.2	
	>+100		+ 85		- 5		+ 30			

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